Guyot

Technical Paper 70 Petroleum Technology 16

UNIVERSITY LIBRARY
JUL 16 1914
PRINCETON

DEPARTMENT OF THE INTERIOR
BUREAU OF MINES
JOSEPH A. HOLMES, DIRECTOR

METHODS OF OIL RECOVERY IN CALIFORNIA

BY

RALPH ARNOLD AND V. R. GARFIAS

WASHINGTON
GOVERNMENT PRINTING OFFICE
1914

The Bureau of Mines, in carrying out one of the provisions of its organic act—to disseminate information concerning investigations made—prints a limited free edition of each of its publications.

When this edition is exhausted copies may be obtained at cost price only through the SUPERINTENDENT OF DOCUMENTS, GOVERNMENT PRINTING OFFICE, WASHINGTON, D. C., who is the authorized agent of the Federal Government for the sale of all publications.

The Superintendent of Documents *is not an official of the Bureau of Mines.* His is an entirely separate office, and he should be addressed:

SUPERINTENDENT OF DOCUMENTS,
Government Printing Office,
Washington, D. C.

The general law under which publications are distributed prohibits the giving of more than one copy of a publication to one person. Additional copies must be purchased from the Superintendent of Documents. The cost of this publication is 10 cents.

First edition. May, 1914.

CONTENTS.

Page.

Introduction ... 5
  Acknowledgments ... 5
  Scope of report ... 5
General statement ... 6
  Factors controlling net production ... 6
    Recoverable oil ... 6
    Efficiency of management ... 6
  Oil pumping ... 7
  Well conditions affecting oil yield and some remedial measures ... 9
Apparatus used for recovering oil ... 10
  The plunger pump ... 11
    Capacity of pump ... 13
  The air lift ... 14
    General discussion ... 14
    Operation ... 16
    Quantity of air ... 20
    Advantages ... 20
    Disadvantages ... 21
  Use of compressed air in engines ... 22
  Other methods for recovering oil ... 22
    Use of agitators ... 22
    Bailing ... 24
    Swabbing ... 24
    Tunneling ... 24
Generation and distribution of power ... 25
  General statement ... 25
  Oil fuel ... 25
  Electricity ... 27
  Natural-gas fuel ... 27
  Wood fuel ... 28
Equipment used in generating and distributing power ... 29
  Steam boilers ... 29
    Efficiency of steam boilers with different fuels ... 30
    Quality of feed water ... 31
  Relative importance of different sources of power ... 34
  Steam engines ... 34
    Steam piping ... 36
  Internal-combustion engines ... 37
    Use of natural gas ... 37
    Utilization of producer gas ... 37
    Efficiencies obtained with natural gas and producer gas ... 38
    Use of crude oil and heavy fuel oil ... 38
    Use of gasoline and engine distillate ... 40

Equipment used in generating and distributing power—Continued. Page.
- Electric motors 40
  - The single-speed motor 41
  - The double-speed motor 42
  - The variable-speed motor 42
  - Cost of pumping by electric power 43
  - Use of motors for rotary pumps 43
- Air-lift pumping plants 44
  - Steam-driven compressors 44
  - Gas-engine compressors 44
- Operation of the plunger pump 45
- Windmills 46
- Swab and bailer 46

Data as to cost of different methods of recovering oil 48
Publications on petroleum technology 54
Index 55

ILLUSTRATIONS.

Page.
FIGURE 1. Delivery pipe of well pumping about 20 barrels of oil a day 7
2. Cross section of working barrel of plunger pump 12
3. Different arrangement of tubing for operating air lifts 17
4. Oil well operated with air-lift pump producing practically nothing but water 18
5. Typical well in Sunset field producing heavy oil and great quantities of sand 23
6. Typical construction of pumping well operated with walking beam. 45
7. Part of Summerland field showing wells on wharves, the wells being pumped by "powers" 47

Original from PRINCETON UNIVERSITY

METHODS OF OIL RECOVERY IN CALIFORNIA.

By Ralph Arnold and V. R. Garfias.

INTRODUCTION.

This report is published by the Bureau of Mines as one of a series describing the investigations conducted by the bureau in an effort to minimize waste in the exploitation of petroleum in lands belonging to or controlled by the Government and to increase efficiency in the use of oil fuel in Government power plants.

ACKNOWLEDGMENTS.

Those parts of the report dealing with power generation, distribution, and economics have been prepared in collaboration with Prof. W. F. Durand, of Leland Stanford Junior University, to whom the writers wish to express their thanks. Acknowledgments are also due to Messrs. W. W. Orcutt, W. R. Hamilton, W. A. Williams, R. S. Hazeltine, A. J. Crites, T. J. Crumpton, Thomas Cox, Charles T. Hutchinson, Chester Naramore, and many others for personal data regarding relative cost of the different methods and their adaptability to varying conditions. To these gentlemen credit is given in the body of the report wherever the specific data obtained from them or their published reports is quoted.

SCOPE OF REPORT.

The factors controlling the economic exploitation of an oil property may be grouped into three divisions—those relating to the intrinsic value of the property as an oil deposit; those pertaining to drilling and recovering the oil; and those controlling its transportation and marketing.

In this paper are discussed the general methods employed in California for recovering the oil when, owing to insufficient gas pressure or other causes, it does not rise to the surface by natural flow. The report comprises a study of different pumping devices and means of generating power to operate them, and summarizes their relative cost and field of usefulness.[a]

---

[a] For discussion of flow from gassers and gushers, see Arnold, Ralph, and Garfias, V. R., The prevention of waste of oil and gas from flowing wells in California: Technical Paper 42, Bureau of Mines, 1913, 15 pp.

GENERAL STATEMENT.

In California a proven oil property may be regarded as a commercially productive reservoir of oil of irregular form lying 200 to 5,000 feet below the surface, and bounded laterally along the property lines by imaginary vertical planes. The deposit may be tapped by wells within the property or in adjacent lands. In either case the cover or cap rock of the reservoir is perforated and the equilibrium of the contents is disturbed by the lateral flow of the oil toward the well. Water-bearing beds, as a rule, occur at different horizons throughout the overlying strata or cap rock and may be present within the reservoir proper or below it.

FACTORS CONTROLLING NET PRODUCTION.

RECOVERABLE OIL.

Although the intrinsic value of an oil property usually is based on the total quantity of oil that theoretically can be recovered, this quantity is seldom, if ever, actually extracted from the underground reservoir. In order to differentiate between the total quantity contained in the sands, that which theoretically can be recovered and that actually recovered, and between the quantity recovered and the volume sold, the terms "oil content," "recoverable oil," "oil recovered" (gross production), and "oil delivered" or sold (net production) commonly are used.

The term "oil content" includes all the oil stored within the boundaries of the tract. A large part of the oil in the producing zones never can be recovered, as friction and other factors prevent its escape from the reservoir rocks. Usually a smaller proportion also is lost in associated sands which, though penetrated by the well, are too poorly saturated to be worked at a profit. As a rule, such isolated sands above and below the main zone eventually become flooded with water.

The term "recoverable oil" represents that part of the stored oil that is extracted when the highest efficiency is attained, the difference between this quantity and the total oil content constituting, in a sense, a theoretical royalty that nature exacts from the oil operator. The efficiency attained in producing oil is measured, therefore, by the ratio of the quantity of "oil recovered" to the "recoverable oil," an ideal condition existing when the two figures are identical. It is estimated that the average actual values of this ratio in California range approximately between 50 and 60 per cent.

EFFICIENCY OF MANAGEMENT.

The "oil recovered" represents to the operating company a definite asset, which, unfortunately, is seldom fully realized. As a rule, the oil is allowed to flow over the ground (see fig. 1) and some is wasted through seepage and evaporation. Furthermore, improper separation from water and wasteful utilization of oil as fuel at wells and pumping plants diminish the net output decidedly. It is probable that 10 to 15 per cent of the total gross production of the State has been wasted through seepage or evaporation, and that between 8 and 10 per cent has been used as fuel in the past, leaving some 80 to 85 per cent as "net production" available for delivery to pipe lines or to the consumer. As in coal mining, there will remain always in an extensive oil deposit a large quantity of oil that never will be recovered. If past conditions prevail throughout the life of the fields, it is no exaggeration to state that of the supply of recoverable oil throughout the oil fields of California not over 40 to 50 per cent will ever be marketed. This loss may be due to a number of causes, such as premature flooding of the main oil reservoir with water, nonrecovery of oil in isolated beds that are never worked, defective finishing of wells, and wasteful production from uncontrolled gushers and gassers.

A remarkable example of the amount of oil that is actually wasted is found in the Kern River field, where a company controlling the land near the junction of the Kern River and a ravine that crosses the field has installed a catch basin to gather the oil wasted by the companies having wells along the ravine. It is estimated that the net "production" of oil from this catch basin for the last eight years aggregates close to 250,000 barrels, or about 85 barrels a day.

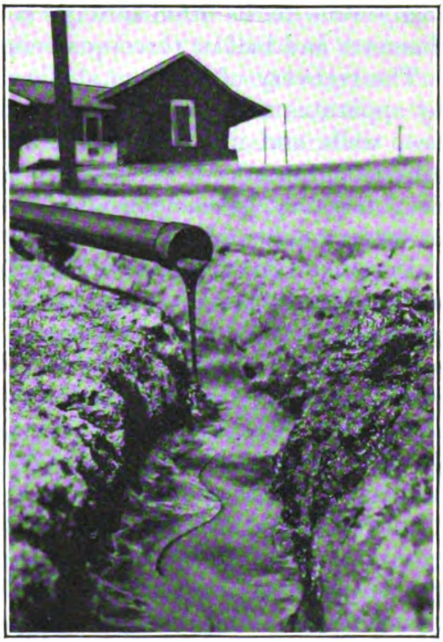

FIGURE 1.—Delivery pipe of well pumping about 20 barrels of oil a day. The oil is allowed to flow in an open ditch across the greater part of this property.

The causes of waste should be kept continually in mind when appraising oil properties, the value of which should not be based on the quantity of oil theoretically recoverable, but on the figures of net production, the only tangible source of revenue to an oil-producing company.

OIL PUMPING.

The majority of oil operators believe that the best means of increasing net production is to add to the number of producing wells, and although in many cases this plan may be advisable, in others it leads

Digitized by Google Original from PRINCETON UNIVERSITY

only to greater expenditure without proportionate return. The financial success of an oil enterprise frequently depends on the factors controlling the ratio between gross production and recoverable oil; that is, on the efficiency attained in the recovery of the oil from the underground reservoir. Efficiency of recovery will assume greater importance as the production of the fields decreases and as uses for crude petroleum are developed.

The pumping of oil under the conditions prevailing in California presents difficulties seldom encountered in mechanical problems of like nature. The character and extent of the difficulties will be evident in some measure if one realizes that a fluid having the consistency of molasses and carrying a large quantity of sand has at many wells to be lifted through a column of tubing 2 or 3 inches in diameter and half or three-quarters of a mile in depth.

The recovery of oil from shallow wells naturally may be effected by apparatus relatively cheaper and simpler than that required for deep wells, and in order to obtain uniformly successful results from different properties it is necessary that the extra cost of operating in deep territory be compensated by a correspondingly greater yield or better quality of oil.

In some of the fields of California wells 200 to 1,000 feet deep, producing about 5 barrels a day, can be operated at a profit if the selling price is as low as 30 cents a barrel, whereas in others, where the oil has to be lifted 3,000 to 4,000 feet, it is not economical to pump the wells unless the yield equals or exceeds 100 barrels a day, or unless the wells contain sufficient gas to assist materially the action of the pump. Some properties in the Santa Clara Valley district afford a striking example of high efficiency. The wells are drilled in 10 to 15 days, tapping the oil sand at about 700 feet; these are pumped in groups of about 20 by means of a pumping "power" operated by a gas engine using natural gas from the wells. The oil produced, owing to its quality, is sold at a price about three times that commanded by the heavy grades in California. The other extreme is well exemplified in the San Joaquin Valley fields, where small quantities of oil are being recovered after more than a year has been consumed in drilling to a depth of over 4,000 feet. Between these extremes the range in types of producing oil properties is great, and the line separating profitable from unprofitable investments fluctuates under the influence of the various factors affecting the oil industry.

One may conclude from the foregoing discussion that the only oil properties worth developing at the present time are those in which oil is encountered in commercial quantities at comparatively shallow depths; but such an assumption is incorrect, as in many instances the increased cost of deep operations is more than compensated by greater thickness of the oil-sand strata, better quality of oil, stronger gas pressure, and the resultant large production and longer life of the wells. In the Coalinga field several wells over 4,000 feet deep, producing oil rated at 0.9210 to 0.8805 specific gravity (22° to 29° B.), are being pumped at a good profit.

WELL CONDITIONS AFFECTING OIL YIELD AND SOME REMEDIAL MEASURES.

Irrespective of the abundance of supply, there are various conditions affecting oil wells that have a controlling influence on their yield. It is a frequent occurrence to find neighboring wells, on land throughout which the underground structure is similar, producing at widely different rates. This discrepancy in production usually is attributed—and not always without reason—to local variations of the reservoir rock, or "sand," some persons claiming that, owing to its lenticular nature, the sand "pinches out;" and others claiming that the sand varies in porosity. In most instances an abnormally low production can be traced to one or more of the following causes: Inefficient management; improper finishing of well; poor condition of casing; failure to perforate casing or inadequate size and number of perforations; obstruction of the bore hole by tools or fragments of débris; failure to exclude water, which sometimes results in the inrush of sand; effect of neighboring wells; and drawing on a secondary sand only.

Although at some wells conditions can not be remedied, and at others the expense incurred would not be compensated by the added production, nevertheless, in most instances, an intelligent study of the trouble and its sources will disclose some comparatively simple means of improving conditions so as to increase the total yield.

The pumping of a well is hindered by the inflow of coarse or medium grained sand. This difficulty often may be eliminated and the net production greatly increased (owing to saving of time and expense in cleaning, etc.) by the use of a screened pipe of the right mesh. On the other hand, if the well produces considerable quantities of clay, or if the oil carries much water, the use of a screen, in most wells, would be very detrimental. Some operators claim that the gravity of the oil also affects the operation of the screen, it being more successful in wells producing the heavier grades of oil.

The indiscriminate use of perforating machines has been the source of much trouble. In the Coalinga field one well about 1,300 feet deep was perforated three times, and when the casing was removed it was found that, except for a few holes, the machine had only indented the casing. In other wells, owing to local brittleness of the casing, the perforator has removed large pieces of it; and in some deep wells, owing to the great weight of the column of tubing to which the perforator is attached, the perforator has cut into or strained the collars so as to cause collapse of the casing.

The best practice is to perforate the casing before it is lowered into the well and to make the size and number of holes as small as practicable, the casing being perforated within the well only when its withdrawal is not advisable.

If a certain well requires more frequent attention than others around it, experiments with different methods of operation and a careful study of its drilling history will ordinarily be advisable. In some wells the condition of the casing may be such as to necessitate its withdrawal and the redrilling of the well, whereas in others a thorough bailing and cleaning may be all that is needed. Of two neighboring wells that have come under observation one has not required pulling the tubing for three years, whereas the other has never produced for more than two or three weeks at a time without the necessity of its being bailed or cleaned.

It is estimated that in wells containing some sand and pumping heavy oil the average life of tubing is about three years and that of the sucker rods two years, although it may be economical to replace either only after its greatest usefulness is past. In the oldest wells in the State little or no effort was made to exclude water before the well entered the oil sands, the wells being lined with light casing which, in many wells, was eaten through by chemical or mechanical action, so that many of the wells had to be redrilled or have the casing replaced by heavier and better material. Both steel and wrought-iron casings are used, and although there is a diversity of opinion regarding their relative merits, it is generally admitted that both are equally suitable for oil-well lining, the prevailing price being the controlling factor in selection.

A carefully kept log of each well is of the utmost importance if the best results are to be obtained during its producing life, and the necessary records and details are better preserved when the property is under one efficient management throughout. Even when logs are kept with care some important details are generally omitted, and few complete records are found.

APPARATUS USED FOR RECOVERING OIL.

Of the 6,223 producing oil wells in California during November, 1913, 217 were flowing. In 247 the oil was lifted by means of compressed air and the remaining 5,759 were operated with the plunger pump. The following table gives a comprehensive idea of the relative importance of the different methods of operating the wells in the principal fields of the State:

Digitized by Google Original from PRINCETON UNIVERSITY

TABLE 1.—*Field report for California oil fields during November, 1913.*

Field.	Number of wells operated by—					Production.	
	Walking beams.	Pumping jacks.	Compressed air.	Natural flow.	Total number of wells.	Estimated net monthly.	Per day per well.
						Barrels.	*Barrels.*
Coalinga	888	23	....	....	911	1,455,000	53.2
Lost Hills	71	....	....	31	102	229,000	74.8
McKittrick[a]	254	27	....	30	311	520,000	55.7
Midway	767	....	50	100	917	2,500,000	90.9
Sunset	221	10	25	[b] 50	306	455,000	49.6
Kern River	898	709	92	....	1,699	840,000	16.5
Santa Maria	224	9	....	[b] 7	240	465,000	64.6
Summerland	....	122	....	....	122	5,000	1.4
Santa Paula	35	295	....	....	330	70,000	7.1
Newhall	7	69	....	....	76	9,000	3.9
Salt Lake	240	....	[c] 50	....	290	200,000	23.0
Los Angeles	....	420	....	....	420	30,000	2.4
Whittier-Coyote	69	61	....	12	142	144,000	33.8
Puente	4	50	....	....	54	2,300	1.4
Fullerton	193	93	....	17	303	650,000	71.5
Total	3,871	1,888	217	247	6,223	7,574,300	549.8

[a] Includes Belridge. [b] Includes wells in which agitators are used. [c] See Table 4.

THE PLUNGER PUMP.

The greater part of the oil produced in California is recovered by the use of the plunger pump (fig. 2), operated with a walking beam, pumping jack, or any other appropriate device. The pumps vary widely in detail of design, but those in general use contain the following essential parts:

The working barrel, generally 66 to 84 inches in length, ground to an inside diameter of 1¾ to 3¾ inches, and manufactured of special cast iron or semisteel, is made to screw on the end of columns of tubing 2, 2½, 3, or 4 inches in diameter, and rests on the bottom of the well or is suspended with the tubing from the casing by means of a tubing catcher or similar device.

The plunger is a tube made of seamless steel and ground to fit tightly inside the working barrel.

The upper or working valve is screwed to the upper part of the plunger and is made of steel throughout, with reversible seat and ball valve of tool steel.

The lower or standing valve, which fits into a tapered recess at the lower part of the barrel, carries a rod that slides through a plug in the lower end of the hollow plunger and carries a nut on its upper end, all as shown in the figure. This construction allows the valve to remain undisturbed during the ordinary reciprocating movement of the plunger, but permits renewal or replacement without necessitating the removal of the tubing.

Other types of pumps, less commonly used in the best practice of the present day, employ various kinds of plunger packing, such as

Digitized by Google Original from PRINCETON UNIVERSITY

leather cups and steel rings, hemp rope, and leather and fiber rings of various kinds. Cups are used where the oil is light and carries little or no sand, as in the eastern fields. In California they are employed only after the common plunger has been slightly worn. For details of construction reference may be made to the catalogues of oil-well supply houses.

The plunger generally is operated by means of steel sucker rods, but in a few types by wire rope or wooden rods. It is estimated that the average life of a steel sucker rod, pumping oil of a gravity of about 0.9655 (15° B.) and containing some sand, is about two years, although in wells producing very heavy oil and great quantities of sand light rods break almost daily. Most of the rods are 20 feet in length, and the number of screw joints is sometimes reduced by welding together two or three such rods. In some properties it is customary from time to time to anneal or soften the rods by heating them in closed ovens and allowing them to cool gradually.

The life of the tubing, at the end of which the pump is placed, varies greatly, but under ordinary conditions it should approximate four years. In some fields producing light oil and no sand, tubing has been used for 10 years and is still in good condition. In crooked holes, in which the oil was heavy and carried sand, the tubing has been known to wear out in one year. One of the most important causes of wear on tubing is its repeated removal from the well. Such removal is necessary in certain territories.

A large number of the difficulties encountered in pumping wells may be traced to the wearing of rods, barrels, and valves by sand, which usually accompanies the oil. The association of oil and sand exists to a greater or lesser extent in all of the San Joaquin Valley fields and becomes extremely troublesome when the cutting action of the sand is intensified by gas under pressure. In wells where conditions accelerate the wearing action of sand, the pump barrels, valve balls, and valve seats have to be removed almost daily. In

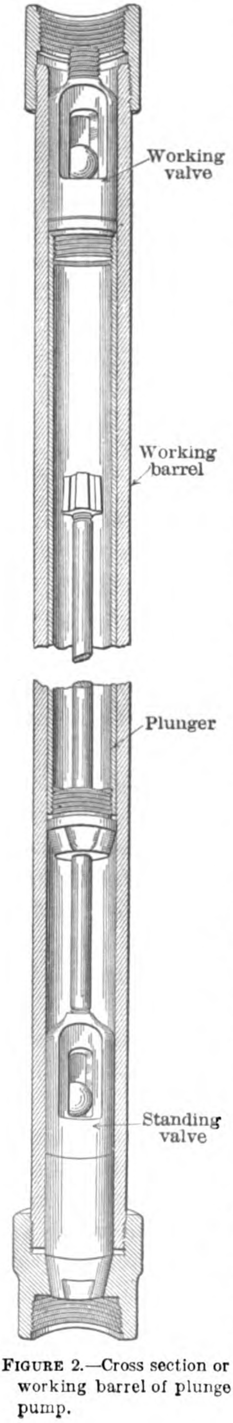

FIGURE 2.—Cross section or working barrel of plunge pump.

properties where no sand is encountered in the wells it is sometimes introduced when the wells are cleaned. This was the case in the Santa Maria field, where the rods were laid on sandy ground, and the sand, adhering to the sticky oil on the rods, was subsequently taken into the well. The trouble was easily eliminated by placing the rods on wooden platforms built for the purpose. If the balls and seats are not greatly damaged they can be ground to a perfect fit by proceeding as follows:

(1) Charge a glass plate with ground carborundum and oil.

(2) Place the steel ball on the plate and the valve seat in position on the ball.

(3) Holding the seat in the hand, describe a figure eight, keeping the seat pressed against the ball and the ball against the plate. In order to ascertain when a perfect fit has been attained, it is necessary only to observe whether the ball adheres to the seat when a partial vacuum is created by placing the mouth against the seat and drawing in the breath strongly.

The frequency of cleaning wells and replacing pump valves and barrels has a most decided effect on the producing time and, therefore, on the quantity of oil recovered and the power consumed. The time spent in cleaning is controlled by the decrease in production, and in some wells the producing time thus lost represents an important part of the economic life.

CAPACITY OF PUMP.

The theoretical capacity of the plunger pump depends on the size of the pump and the length and number of strokes per minute. The pump in most common use has an internal diameter of 2¾ inches. The pumping stroke varies from 20 to 35 inches, the average being about 23 inches. The number of strokes is from 15 to 30 per minute, the greatest number of wells in the State being pumped at an average speed of 20 strokes per minute.

Assuming these average pumping conditions (a 2¾-inch pump working at a speed of 20 strokes per minute, with a length of stroke of 23 inches), the ideal daily capacity, without allowance for leakage, will be about 400 barrels. Although the pumping speed and the length of stroke on which these figures are based are exceeded in actual practice, it is doubtful whether, if the losses due to leakage be included, the average working capacity of a 2¾-inch oil pump, in wells of average depth and in which gas does not help the action of the pump, can be much greater than 400 barrels a day. In actual practice, owing to the varying quality of the oil, the percentage of sand and sediment, and the generally poor condition of tubing and pumps, with consequent leakage, the results obtained are generally much lower than this figure. It should be remembered, however, that a 400-barrel well contains, as a rule, enough gas to alter materially these figures and increase greatly the over-all production.

The figures in Table 2 represent actual conditions in wells of different depths, taken at random, and serve to emphasize the fact that there is no set rule to be followed in operating pumping wells and that, in order to obtain the best results, an individual study is necessary.

TABLE 2.—*Records of operation of pumping wells.*

Depth.	Strokes per minute.			Production.	Frequency of cleaning.	Frequency of replacing plungers and barrels.	Frequency of replacing seats or balls.	Age of well.
	Low.	High.	Average.					
Feet.				*Barrels.*	*Months.*	*Days.*	*Days.*	*Years.*
700	....	....	18	15	....	....	....	....
900	....	....	30	5	6	270	120	6
1,000	....	....	20	40	(*a*)	90	7	14
1,500	16	20	19	30	....	18	18	2.5
2,000	19	22	20	100	....	20	18	2.6
2,500	20	30	25	200	24	30-180	30-180	12
3,000	20	26	23	180	12	30-180	30-180	12

[a] Every 7 days.

THE AIR LIFT.

GENERAL DISCUSSION.

When the value of the maximum quantity of net oil recovered by by means of the plunger pump does not render the operation profitable, it becomes necessary to increase the yield, and in such cases air-lift pumping can be sometimes employed advantageously.

The operation of the air lift depends on the buoyancy of aerated liquids. To obtain the desired results, air is pumped into the well through a small pipe to a convenient point below the surface of the liquid, where it is allowed to discharge into a larger pipe through which the aerated fluid rises above ground. It is important that air be admitted to the fluid in a finely divided state and in such a manner as to realize the full cross-sectional area of the discharge pipe for the passage of the liquid. The pumping of water by this method has been successfully accomplished for many years and most of the experience gained with the air lift has been obtained in pumping water. It is claimed that clean oil with a gravity of about 0.8641 (32° B.) can be lifted by air almost as readily as water, but that clean oil with a gravity of 0.9589 (16° B.) or heavier generally can not be recovered economically. However, a well in the Santa Maria district, producing oil of about 0.9859 (12° B.), is said to have operated successfully with air.

The successful operation of the air lift for pumping oil and water mixtures depends upon a number of factors, most important of which are: (1) The height of the column of fluid that the aerated mixture has to overcome or the height from air inlet to the surface of liquid

Digitized by Google Original from PRINCETON UNIVERSITY

in the well. This is known as submergence. (2) The total vertical distance from the point of admission of air to the point of discharge, the ratio between these two quantities representing the percentage of submergence. (3) The lift or distance from the surface of the liquid to the level of discharge. (4) The air pressure. (5) The pressure of gas in the well. (6) The gravity of the oil. (7) The percentage of water in the oil. (8) The quantity of sand in the oil.

As shown in Table 4 this method is used extensively in the Kern River field, where conditions are very favorable for its successful operation. The wells in this field are about 1,000 feet deep and produce oil with a gravity of 0.9722 (14° B.) and containing 80 to 85 per cent of water, the submergence in most cases being between 250 and 400 feet, or about 33 per cent.

The quantity of air should be carefully regulated, the best results being obtained with the minimum volume of air necessary to cause the liquid to flow in a constant stream. Owing to the extra pressure needed to overcome the friction and inertia, the starting pressure is about double the working and calculated air pressure. The variations in the level of the liquid in the well are indicated by pressure gages on the compressor and air side of the valve that controls the air supply.

The gas that sometimes accompanies the oil helps the action of the air lift by diminishing the required air pressure, and in order to utilize all the available gas pressure it is customary to place a packer between the tubing and the casing, thus forcing the gas to flow through the discharge pipe. Wells of the same depth may require different pressures, and in order to obtain the best results a careful study of the special conditions will be desirable. In the Kern River field, wells about 1,200 feet deep are pumped with air under a pressure of about 180 pounds to the square inch.

In most fields where the use of compressed air proves most beneficial, the oil and water occur in somewhat well-defined layers—a lower indefinite layer of water, an upper one of nearly pure oil, and an intermediate layer consisting of a mixture of oil and water. In nearly all such fields the water surface stands at a well-defined plane; below water is obtained, above the percentage of pure oil increases with the distance above this plane. It is possible, therefore, providing the necessary submergence is available, to pump either water or oil, or within limits, any combination of the two, by regulating the location of the air inlet in relation to the water surface. If air is admitted to a stratum where water and oil are mixed the churning action caused by the air has a tendency to mix them more thoroughly and to form emulsions. This result is avoided sometimes by pumping the water and oil in the same well separately, using the air lift for the water and removing the oil by means of a plunger pump.

The conditions under which the use of an air-lift pump becomes advisable can be ascertained only after a careful and intelligent analysis of all factors affecting the operation of the property, and usually it will be found economical to seek the advice of a competent mechanical engineer before incurring the necessary expense for development. The high initial cost renders the selection of compressed-air machinery of special importance, and the proper choice and disposal of air lines and well tubing, the regulation of air pressures, and the proper determination of the many factors involved in power-plant economics are each problems of such importance that their solution can be best determined by a technically trained man familiar with local conditions.

In general, it may be stated that air-lift pumping in the oil fields should be used as a last resort when the ordinary methods are no longer effective, and should be restricted to territory where considerable water accompanies the oil and there is ample submergence.

OPERATION.

The different arrangements of tubing for operating the air lift are shown in figure 3. In the figure A shows a lift arrangement comprising an annular air tube, and B and C show an arrangement utilizing a central air tube. In the device shown at C the operation of the air lift is regulated, and to some extent improved, by admitting air under pressure in the annular space between the casing and the tubing. The arrangement of tubing represented by D, in which two separate air pipes are used, has not proved satisfactory. At E is shown a modified type of air-lift pump used successfully in the Kern River field. The air is admitted into the discharge pipe by means of the foot piece, as shown, and pumps the water; the oil above is removed by means of the plunger pump.

In most air-lift pumping the air is conveyed into the well through a 1-inch pipe, under a pressure sufficient to overcome the weight of the column of liquid representing the submergence, and is discharged into a 2½ or 3 inch tubing through a pump head or foot piece (C, fig. 3) which controls the distribution of the air. As the column of liquid becomes aerated and consequently lighter, the pressure can be correspondingly reduced. This method has given satisfactory results in some properties in the Kern River field. In at least one well in the Salt Lake field two plunger pumps are utilized in similar manner, one pumping almost clear water, while the other skims the oil higher up. In some wells it may even prove practical to use two separate air lifts, one for the water and the other for the overlying oil.

When large quantities of fluid are being removed from several wells within a small area, an underground migration of oil and water toward certain wells is established, and other near-by wells may be deprived of the oil and tap only the underlying water (see fig. 4). If large quantities of water are pumped from these "water" wells by

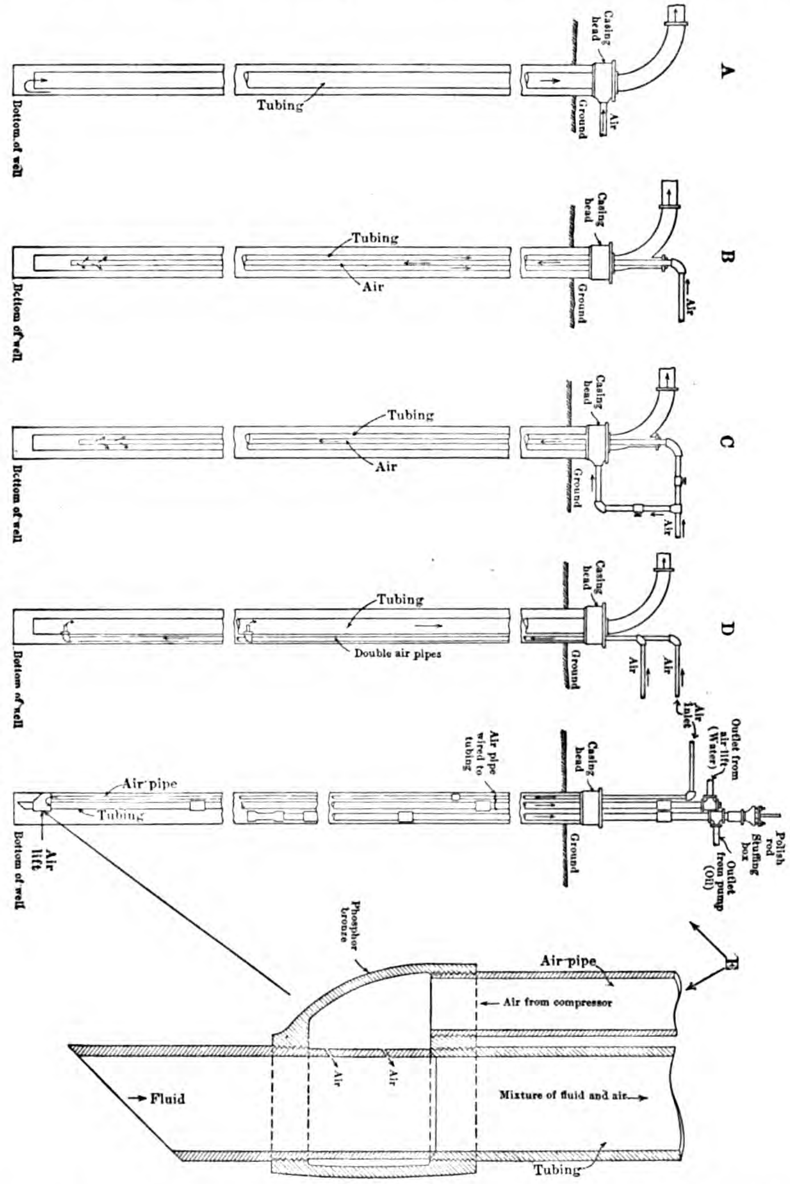

FIGURE 3.—Different arrangement of tubing for operating air lifts.

means of the air lift, the level of the water in the immediate vicinity will be somewhat lowered and the proportion of pure oil pumped in "oil" wells materially increased. The operation of such water wells, sometimes known as "key" wells, has therefore a marked influence on the oil productivity of the surrounding area.

Several formulas have been derived in an effort to develop a theory of the air-lift pump on a mathematical analysis of the problem, but these apply only to conditions that prevail in pumping water and do not necessarily apply when water constitutes only a fraction of the total volume of fluid pumped. Davis and Weidner [a] state that "by varying the percentage of submergence, and therefore the lift, the length of pump remaining constant, the maximum efficiency (pumping water) is obtained at approximately 63 per cent submergence for all rates of input or discharge."

The data collected in the oil fields apply only to local conditions, and results are necessarily dissimilar. In some instances the best results have been obtained with a submergence of about 60 per cent. In the Kern River field it has been found that the best results are obtained with a submergence of between 30 and 40 per cent, but owing to the varying nature of the oil-and-water mixtures and to the many local modifications necessary in operation it is doubtful whether even future investigations will warrant a single value for this ratio. In general, when mixtures of water and oil are being pumped pipes of about 2½ inches diameter and somewhat greater submergence than the best value for water give the most satisfactory results.

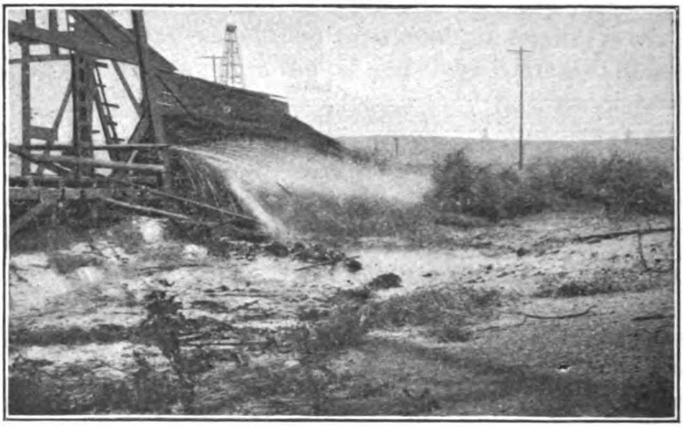

FIGURE 4.—Oil well operated with air-lift pump producing practically nothing but water.

Hutchinson [b] states that in the Kern River field a typical well, about 1,200 feet deep, is operating with an air pressure of 182½ pounds to the square inch at the surface and a 30 per cent submergence.

---

[a] Davis, jr., G. J., and Weidner, C. R., An investigation of the air-lift pump: Bull. of the University of Wisconsin, 1911, p. 524.

[b] Hutchinson, C. T., Oil-pumping practice at Bakersfield: Western Engineering, vol. 1, August, 1912, p. 355.

Original from PRINCETON UNIVERSITY

Rix [a] notes an instance in the Kern River field as follows:

> In a test of air-lift systems in the Kern River field, made by the Peerless Co., pumping a mixture of water with 20 per cent oil, at an average lift of 470 feet, with an average submergence of 40 per cent and an average length of discharge pipe of 800 feet, they found as the average of many tests:
>
> Air pressure, 152 pounds.
> Free air per minute, 140 cubic feet.
> Gallons of fluid per minute, 93.
> Cubic feet of free air per gallon of fluid, 1.5.
> Ratio of free air to fluid pumped, 11.
>
> Ninety-three gallons of fluid per minute is equivalent to 3,400 barrels a day.
>
> The above pumping was done through 3-inch tubing, with 1¼-inch air pipes, and both the straight-air systems, as shown in illustrations (Type "E") and also two other so-called patented systems, with the result that no gain was shown by the patented systems.
>
> While on this subject it might be well to say that one well was piped as many as 13 times, using the straight-air system, and after each piping better results were shown; in fact, the variation in pipe sizes and ratio of submergence, all within reasonable limits, show a very marked variation in economy.

Table 3, following, gives the results obtained by Ivens in wells in Evangeline, La.: [b]

TABLE 3.—*Summary of results of pumping tests at wells 12, 30, and 32, at Evangeline, La.*

Duration of tests, hours	6.00
Mean (total) indicated horsepower	151.10
Mean (total) water horsepower	25.14
Mean (total) air horsepower	129.05
Total gallons of fluid per hour	6,168.00
Total barrels of fluid per hour	146.87
Total barrels of oil per hour	16.17
Size of air lines in well, inches	1.25
Barometer reading, inches of mercury	29.95
Dimensions of compressors, inches	10 by 22 by 16 by 20
Number operated	1
Kind of fuel used	crude oil
Barrels of fuel used per hour	1.45
Price of 1 barrel of oil at time of test, dollars	0.90
Cost in fuel of producing 1 barrel of oil, dollars	0.07

	Well 12.	Well 30.	Well 32.
Weight of 1 gallon of fluid, pounds	8.50	8.65	8.70
Temperature of fluid, ° F	118.50	120.20	114.50
Percentage of salt water in fluid	87.20	88.30	86.90
Percentage of sand in fluid	1.30	1.50	1.80
Percentage of crude oil in fluid	11.50	10.20	11.30
Barrels of oil per hour	6.44	4.83	4.90
Specific gravity of oil	0.87	0.90	0.90
Total depth of well, feet	1,705.00	1,920.00	1,901.00
Size of casing, inches	6.00	6.00	6.00
Size of discharge line, inches	4.00	4.00	4.00
Height above ground to which fluid was pumped, feet	17.50	18.00	18.50
Total length of vertical discharge line, feet	1,025.50	1,516.30	1,513.00
Total length of vertical air line in well, feet	992.58	1,494.20	1,493.00

---

[a] Rix, E. A., Air-lift pumping of fluids: The Oil Industry, vol. 3, June, 1910, p. 8.
[b] Ivens, E. M., Tests upon compressed-air pumping systems of oil wells: Trans. Am. Soc. Mech. Engrs. vol. 31, May, 1909, pp. 311–332.

QUANTITY OF AIR.

The consumption of air varies with change of any of the conditions affecting the efficiency, such as submergence, height of lift, quality of the oil, quantity of water and sand in suspension, and volume and pressure of accompanying gas. Representative tests have shown a consumption of eleven or twelve volumes of free air to one of fluid pumped, and for less efficient operation the proportion of air to fluid may be fifteen to one, or more.

The transmission and application of energy by the use of compressed air always involves a low over-all efficiency. Between input to the compressor and net work in terms of oil lifted, the efficiency will average only about 30 per cent.

In the Kern River field, with a 35 per cent submergence, which has proved on the whole most satisfactory, the consumption per well per minute has averaged about 140 cubic feet of free air, compressed to a pressure of 152 pounds per square inch. After estimating the theoretical required volume of air, an adequate margin of safety should be allowed in calculating the quantity of air needed in actual practice.

ADVANTAGES.

The principal advantages of the air-lift system are its great capacity, low operating cost, and low cost of upkeep at the wells from absence of moving parts, thus making it especially suited for handling oil-and-water mixtures carrying a considerable quantity of sand, which would rapidly wear valves and pump barrels.

In properties where the oil produced contains considerable water the exhaust steam from the compressor plants can be carried through pipe coils and utilized for heating the fluid to a temperature at which the water and oil will separate. This method of heating oil is inexpensive, lessens the work on the engine condensers, and saves the consumption of fuel oil needed to realize the same purpose. A temperature of 150° F. can be thus maintained in the heating plants, giving excellent results in dehydration, certain emulsions containing 50 per cent of water before treatment have been reduced to a point showing not over 2 per cent.

The air lift generally works in a satisfactory manner when not over 20 per cent of sand accompanies the oil. Thompson [a] notes that a fluid mixture containing as much as 50 per cent of sand has been removed by the air lift. The presence of clay in suspension generally occasions much more serious trouble.

---

[a] Thompson, A. B., Petroleum mining, 1910, p. 296.

DISADVANTAGES.

Some oil operators maintain that although the use of compressed air will, beyond reasonable question, increase the production in comparatively shallow wells for a limited time, nevertheless, after a certain amount has been recovered, the oil seems to recede. This claim is seemingly substantiated by the fact that at times neighboring wells increase in production, while those operated with air decline. This condition, however, may be due to a number of factors other than the action of the air.

Another factor that limits the use of the air lift is the depth of submergence required. The extraction of mixed water and oil in large quantities from small areas lowers the water level, thus increasing the height of lift and the degree of submergence necessary to maintain a fixed percentage. The lowering of the pipe to meet these conditions must ultimately bring it to the bottom of the well, thus leaving a residue of liquid which can be removed only by an increasingly uneconomical use of the apparatus.

In one 2,900-foot well operated with compressed air the production was less than that obtained with a 3-inch plunger pump. The starting pressure required was 1,400 to 1,500 pounds per square inch and the working pressure about 750 pounds.

In wells in which there is not enough fluid to allow continuous operation it becomes necessary to apply the air intermittently. Such operation, however, may cause sand to run in and give serious trouble. In such cases it is generally best to use the plunger pump, say every 24 or 48 hours, and recover only the accumulated oil, an operation that is often spoken of as "skimming." The air lift is not generally satisfactory for pumping heavy, viscous oil, as the air and oil do not mix readily, and the air escapes carrying little or no oil with it. The violent agitation of the fluid, caused by aeration, leads at times to the formation of emulsions, which are separated with difficulty. As a rule the greater part of the water and oil separates if the mixture be allowed to settle after heating, but some emulsions require either an electric treatment [a] or partial refining in order to separate their constituents. Because of the general characteristics of air-pressure machinery and appliances, the high initial cost and the sums invested in existing installations, the use of air-lift pumping is to be considered only where the wells are numerous, not widely scattered, and not of excessive depth, and when the fluid in the wells rises high enough to provide the necessary submergence and carries a large admixture of water, but not excessive proportions of sand and clay.

---

[a] Wright, A. C., Water emulsion in crude petroleum: Western Engineering, vol. 1, June, 1912, p. 207.

USE OF COMPRESSED AIR IN ENGINES.

A special plan developed to meet peculiar conditions is now in practice in the Salt Lake field. On one property there are 52 wells, averaging 1,200 feet deep and producing oil with a gravity of 0.9655 (15° B.) and large quantities of gas. Considerable sand accompanies the oil, necessitating frequent cleaning of the wells. The boiler water contains a large percentage of incrustating solids, necessitating the cleaning of the boilers on an average of every eight days. As there is no market for the gas, the cost of fuel is a small item in the total cost of operation. The property was first operated entirely with steam, but its use became impracticable owing to the poor quality of the boiler water and the large amount of condensation that took place in the long steam lines, the wells being scattered over 500 acres of territory. It was found, however, that steam installation could be replaced advantageously by using compressed air in place of steam for the operation of the engines. This plan was adopted and has been in successful operation for about two years. The air is compressed to a pressure of 38 pounds per square inch in three 1600-foot per minute, steam-driven, condensing, cross-compound, single-stage, duplex air compressors, and is reheated at the wells to a temperature of about 200° F. by means of a small burner using natural gas as fuel. As steam was necessary to operate the engines for drilling or cleaning the wells, and for heating oil for its separation from water, all the steam equipment was retained. Much of the boiler trouble has been eliminated by using condensed water from the compressors, it being estimated that 24 wells are now pumped with the same boiler that formerly handled 10.

OTHER METHODS FOR RECOVERING OIL.

USE OF AGITATORS.

In the old Sunset field wells that have a strong gas pressure produce more sand than any others in the State, it being estimated that sometimes as much as two-thirds of the gross yield of the wells is sand (see fig. 5). One well alone produced over 110,000 cubic feet of sand in about four years, and another has yielded almost as much in two years. The yield of sand gradually decreases with the age of the well, but at no time entirely ceases. These peculiar conditions—soft sand in great quantities accompanying the flow, heavy oil, and strong gas pressure—make the problem of well operation in this field difficult.

A method of handling the wells that has proved highly successful was discovered by accident several years ago. This method consists in intermittently agitating, by means of a smaller "agitating string," the sand within or below the casing that penetrates into the oil sand. The inner string is usually of 7⅝-inch diameter, the well being finished as a rule with 9⅝-inch casing. If the sand is thus kept loosened by agitation the gas pressure is strong enough to cause the well to flow. When the gas pressure weakens compressed air is forced down the agitating string, usually with successful results. It has been found impracticable, for various reasons, to pump oil containing much sand, and the agitation method, therefore, has been the salvation of parts of this field.

The producing wells are 400 to 1,000 feet deep, the oil, of a gravity of about 0.9859 (12° B.), flowing between the agitator string and the casing. The entire string must be kept free and is moved often enough to keep the well flowing. The size of the agitator string varies with the volume of gas in the well. If the volume is considerable, the string may be comparatively small, larger strings being used as the gas pressure decreases. As much as 66 per cent of sand flows with the oil in this part of the Sunset field. It will be a difficult task to

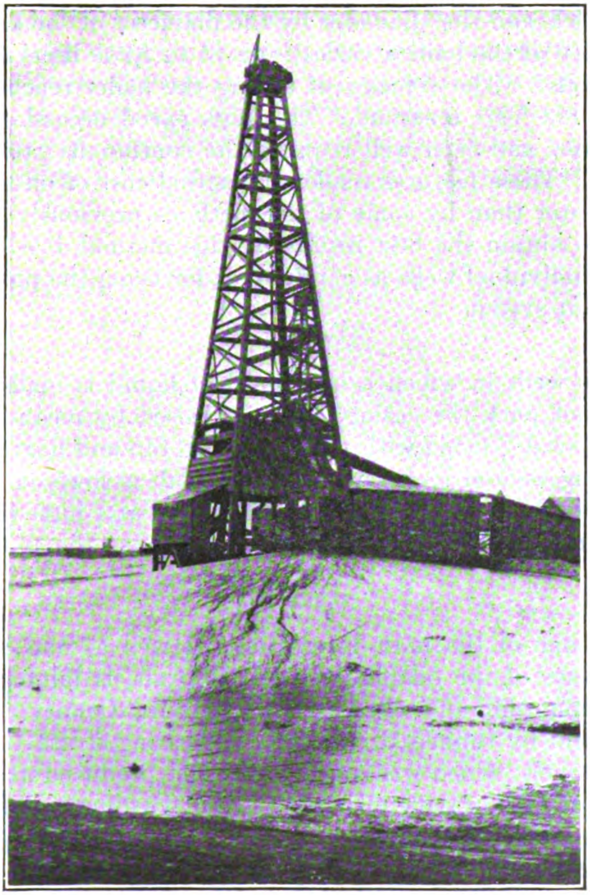

FIGURE 5.—Typical well in Sunset field producing heavy oil and great quantities of sand. Note sand cone around derrick and agitator string suspended from casing block.

Original from PRINCETON UNIVERSITY

recover the oil economically by the present method when the gas pressure subsides, and it is possible that the use of the Russian bailing method may then be found necessary.

BAILING.

In some oil fields, notably those of Baku and Roumania, so much suspended sand accompanies the oil that all apparatus of which plungers and valves form a part is useless for pumping, and the oil as a rule is raised by bailing. The maximum length of the bailer is limited by the height of the derrick and the diameter by the diameter of the inner casing. The capacity of the bailers varies from 15 to 1,250 liters (0.09 barrel to 7.9 barrels). The velocity of raising the bailer reaches at times 10 meters (33 feet) a second. This high speed necessitates considerable power, and each well requires the continuous presence of an attendant. These features render the actual cost of oil recovery by bailing greater than by some of the methods previously mentioned. In order to obtain the best results by this method, it is essential to study the individual wells as carefully as for using the plunger-pump or the air-lift system.

SWABBING.

In a few wells in which a high level of liquid is maintained and sand will not pack the casing the oil is raised by means of an iron piston or "swab" fitted with a lift valve on top and having a rubber packing ring several inches wide. The swab is lowered on a steel-wire rope to the bottom of the well and raised at a high velocity, the oil above the plunger being thereby lifted over the mouth of the casing.

TUNNELING.

Perhaps one of the most interesting, as well as one of the least known phases of the oil industry in California, is mining for oil in Sulphur Mountain and elsewhere in Ventura County and in the Coalinga field by tunnels driven into oil-bearing strata. The oldest of these tunnels, which was dug in 1861 and produced at first about 60 barrels of high-gravity oil a day, is still yielding small quantities of oil and considerable water.

With the improved methods of mining now at hand it is possible that commercial success could be obtained by systematic tunneling to some of these reservoirs, at a cost not greatly exceeding that of the average deep oil well. The mechanical troubles that are usually encountered in drilling would be minimized by this method, and all those encountered in pumping would be avoided, as the recoverable oil would usually gravitate out of the sand. One drawback of this method, pointed out by Prutzman,[a] is the escape of the gasoline from the oil before it is recovered outside the tunnel.

---

[a] Prutzman, P. W., Petroleum in southern California: Cal. State Mining Bureau Bull. 63, 1913, p. 32.

GENERATION AND DISTRIBUTION OF POWER.

GENERAL STATEMENT.

The primary sources of power available for service in the oil fields are oil, natural gas, water impounded on the adjacent mountains, and wood.

Oil, natural gas, and wood are made to serve as sources of mechanical power by means of the familiar steam engine. Oil, or its distillation products, and natural gas may be made to serve more directly by use in the internal-combustion engine. Water impounded on the mountains may serve by means of the hydraulic power plant, combined with electrical transmission and application at the point of use.

Oil, gas, or wood may similarly be made to serve as a source of power developed at a central station and distributed and applied by electrical means, by mechanical means, or by compressed air.

OIL FUEL.

Oil used as fuel for boilers is drawn directly from local sources in the most convenient manner, and therefore includes the various grades found in the oil fields. The gravity of such oils may range from 0.9929 to 0.9032 (11° to 25° B.), or more, but for the most part is from 0.9722 to 0.9459 (14° to 18° B.). If the gravity ranges much above 25° B., the market value of the oil renders desirable the purchase of outside fuel oil of heavier gravity, or natural gas, if available, rather than the use of the relatively high-priced product under steam boilers.

The heating value of the oils commonly used ranges from 18,000 to 19,000 B. t. u. per pound. Although the heating value of oils increases, as a general rule, with the increase in Baumé gravity, such increase does not seem to be in accord with any definite law and, in any event, is usually at a lower rate than the decrease in specific gravity. It results that, as a rule, the heating value per barrel decreases with the increase in the Baumé readings, and as oil is sold by the barrel it follows that, in relation to the unit of sale, oil that has high gravity by the Baumé scale contains less heat than that of low gravity and is therefore less effective when used directly for fuel. Oil of a gravity of 0.9032 (25° B.) will weigh about 317 pounds per barrel, and oil of a gravity of 0.9655 (15° B.) about 338 pounds per barrel. If the heating values should be about the same, the heavier oil would show an advantage per barrel of about 7 per cent over the lighter oil. If the lighter oil should have a heating value per pound of, say, 4 per cent more than the heavier oil, an advantage of about 3 per cent per barrel would still remain with the heavier oil.

As elsewhere noted, much of the oil as it comes from the well carries a considerable percentage of water as well as sand in varying degrees. Sand in considerable quantity is liable to clog the burners, and water in large quantity will render the action of the burner irregular and subject to possible interruption, so that gas may form within the furnace and subsequently ignite and explode. Although the commercial limit of water content for fuel oil is usually taken at about 2 per cent, considerably more tolerance will naturally prevail in the use of oil directly at the well and for home consumption. If, however, the sand content or the water content exceeds moderate limits, it is practically necessary to bring about a separation, either by gravity settling or by more direct means, before feeding the oil to the burners.

The combustion of oil in the furnace is effected by means of a burner which breaks up or atomizes the oil, the least possible amount of air or steam being used. The spray, heated by the products of combustion within the furnace, flashes into vapor, and this vapor, a mixture of hydrocarbons, becomes dissociated as its temperature rises still higher. In the presence of the oxygen provided by the air introduced at suitable inlets, combustion then takes place and heat is liberated. With proper air supply and temperature conditions the fuel should burn with a clean, bright flame and be completely consumed without smoke or soot. The burner should be of a type that is easily removed and cleaned, has a considerable range of adjustment without removal, and throws a flame proportionate to the size of the fire box.

The burners may consist of simple improvised pipe arrangements or of representative fuel-oil burners of the many types on the market. The oil is fed to the burners by pump or directly by gravity flow, and steam is commonly used as the atomizing agent. It may be noted that if an air lift is used, compressed air could be employed for atomizing whenever the air lift is being operated. The advantage of air over steam would be doubtful, however, and steam will presumably remain the accepted agent for atomization as long as oil is employed directly as a boiler fuel.

The expense of atomization can not be overlooked in a study of the economics of power production. Expressed in terms of the steam generated, the proportion required for atomization in no usual case will fall below 3 per cent, and may easily rise to twice that value, or more. If the requirement be expressed in terms of steam in relation to oil, then every pound of oil requires for atomization one-third to two-thirds of a pound of steam.

In the general regulation of boiler operation, special attention should be given to the air supply and to reducing the excess air introduced into the furnace to the smallest possible volume. Attention to this point will result in marked economy as compared with the ordinary haphazard way of firing. With due care, the excess air may be reduced to 20 or 30 per cent, or even less. With neglect, it may rise to 100 per cent, and more, with corresponding serious loss in the furnace efficiency.

ELECTRICITY.

The situation of many of the oil fields of California near the Sierra Nevada Mountains, where perennial streams are the source of electric power, accounts for the wide use of electricity throughout the San Joaquin Valley fields. The Sierra Nevada forms the eastern rim of the valley, and the oil fields are situated on the western edge of this depression, between the mountains and the important cities on the coast. The situation of the fields greatly facilitates the transmission of the current and lessens the expense for the proper looping of the lines. A 60,000-volt loop starts from a substation in the San Joaquin Valley and runs through the Coalinga, Lost Hills, Belridge, McKittrick, Midway, and Kern River fields, thence north to the point of beginning, a distance of 370 miles. The secondary lines in the oil fields are three-wire lines and supply three-phase current; commonly there is a fourth line for neutral, the voltage being 11,000 volts between main lines and 6,600 to neutral. These lines are often ended in loops in the fields, having pole-top switches about every 3 miles, thus allowing the segregation and elimination of any section in trouble and continued service to other sections.

NATURAL-GAS FUEL.

Natural gas, as found in the oil fields of California, consists largely of methane or marsh gas (CH_4) with small proportions of the higher paraffin hydrocarbons, illuminants, nitrogen, and oxygen. Its heating value averages about 1,000 B. t. u. per cubic foot. Under suitable cooling and compression a small proportion of the lighter hydrocarbons forming the gasoline group may be condensed at some wells. It may be noted that the natural gas of the Coast fields is relatively much richer in gasoline constituents than that of the Valley fields.

This possible source of gasoline is assuming increasing importance in California, and if the flow of gas at a given property is considerable, the gas should be analyzed in order to ascertain whether it carries a sufficient percentage of such hydrocarbons as to warrant the installation of a plant for producing gasoline. A steady daily production of about 400,000 cubic feet of gas, containing about 1 gallon of gasoline per 1,000 cubic feet, will generally justify the installation of a plant unit at a cost of about $10,000. After the gasoline has been extracted, the remaining gas can be used for boiler fuel or internal-combustion engines, with only a slight change in its general physical properties or thermal value per cubic foot as compared with the original gas.

Natural gas as a fuel under boilers is burned in simple though somewhat specially developed types of burners. The principal details of design are the proper distribution of burners over the grate or floor of the furnace, and the arrangements for regulating and distributing the air admitted through or around the burners to supply the necessary oxygen. To produce complete combustion, each volume of natural gas should be mixed with 11 to 12 parts of air, a mixture that can be obtained, if the gas pressure is very light, by the inducing action developed by injecting a small quantity of compressed air as the gas passes through the short air space between the gas nozzle and the furnace. The volume of compressed air required is very small.

From a line with a pressure of 80 to 100 pounds of air a hole with a diameter of about three-sixty-fourths of an inch will provide sufficient induction for the air supply of a 70-horsepower boiler.

As a further aid in handling natural gas from the average pumping well at the relatively low pressure of 4 to 10 inches of water, automatic traps are sometimes used to raise such pressures up to 12 or 15 inches of water.

Gas pipe lines should have bleeders or traps for the removal of condensation placed at low points and so designed that the needed volume of gas will reach the furnace at the required pressure. Natural gas, when burned under proper conditions, furnishes a clear smokeless flame, permitting excellent distribution over the heating surfaces of the boiler. Such a flame is free from soot, and is generally conducive to good boiler economy. When properly managed, natural gas is perhaps the nearest approach to an ideal boiler fuel that nature has provided, and the attention of all operators is strongly called to the possibilities of natural gas, not only because its utilization will increase the efficiency and life of steam boilers but also because it has too often been allowed to escape with little or no effort made to prevent the waste of its available heat energy.

WOOD FUEL.

Wood is used for fuel only at wells in "wildcat" territory, and even there it may often pay to haul oil rather than to depend on uncertain or irregular supplies of wood.

Wood, when newly felled, may contain 40 to 50 per cent of water. Commercially dry wood contains not far from 25 per cent of moisture. The heating value of a pound of wood averages about 5,000 or 6,000 B. t. u. or, roughly, from one-fourth to one-third that of a pound of oil. The unit of sale, however, is the cord of 128 cubic feet, and the heating value of such a unit depends on many conditions, such as kind of wood, moisture content, specific gravity, size of sticks, and closeness of piling. Most firewoods weigh 2,000 to 4,000 pounds per cord, averaging somewhat less than 3,000 pounds. Thus, roughly, a cord of wood should equal in heating value 2 to 3 barrels of oil.

EQUIPMENT USED IN GENERATING AND DISTRIBUTING POWER.

STEAM BOILERS.

The steam boilers commonly used in the California oil fields are of two types—the locomotive and the plain, cylindrical, externally fired, shell or fire-tube boiler. The former is somewhat more expensive than the latter in first cost, its upkeep is likely to be somewhat greater, and it is liable to more serious trouble if the feed water carries a large proportion of scale-forming minerals. It is also more sensitive to neglect, to variations in the water level, and to the general accidents of service. On the other hand, the cost for setting is less than for the plain shell boiler, and it is more conveniently and cheaply moved from one well to another. On the whole, the externally fired shell boiler is most commonly employed for general service in the field. Neither type is inherently superior in efficiency to the other, efficiency depending primarily on the details of setting, heat insulation, and conditions of operation, rather than on the fundamental difference of type.

The sizes commonly found in the oil fields are those rated at 40 or 45 and 60 boiler horsepower, containing, respectively, about 400 or 450 and 600 square feet of heating surface. The steam pressures carried may vary from 80 to 125 pounds gage, and the weights range about 8,000 pounds for the smaller and 12,000 for the larger sizes.

The typical boiler for power purposes during the drilling of a well by the standard method is of the shell or externally fired type of the 40 or 45 horsepower size. If, however, the drilling is to be done by rotary tools, two of the smaller boilers or one of the larger or 60-horsepower size will be required. After the drilling of the well has been completed, the demand for power to operate the usual individual oil-well pump is much reduced. The boiler, however, may be, and at many wells is, allowed to remain to provide steam for pumping. However, especially when a property includes several wells not too widely scattered, it may become economical to consolidate two or more of the small boilers into a battery at some central point, and to distribute steam for heating, pumping, redrilling, and cleaning throughout the territory. The drilling boiler may be shifted after the well has been drilled, so that the locomotive type may, with advantage, be employed for the drilling.

The externally-fired shell boiler is commonly set on brick walls to form a furnace and often has a wood crib outside, the space between being filled with adobe or oil sand for heat insulation. The locomotive type is commonly left without nonconducting covering, a procedure that necessarily conduces to poor economy as compared with a well-insulated boiler.

The above remarks as to type and size of boiler refer especially to those used in the field and at the individual wells in connection with the drilling and recovery of the oil. At a few of the large properties central power stations are used. From these heat or power, or both, in the form of steam, air, or electricity, are distributed over considerable areas. Ordinary power-plant practice prevails also at the pumping plants for handling oil in pipe lines, at refining plants, and at various points in the history of oil after it leaves the well. In all such plants typical and standard central power-station practice is found, the boilers being commonly of the water-tube type and in units of 100 horsepower and upward.

EFFICIENCY OF STEAM BOILERS WITH DIFFERENT FUELS.

The steam boiler, considered as a means for liberating heat energy by the combustion of fuel and the transfer of such energy into the heat of steam, may operate at efficiencies below 82 to 83 per cent. Under the conditions that prevail in the oil fields, especially at the wells, in view of the type and size of units, it is not to be expected that efficiencies much exceeding 70 per cent will be realized, and doubtless in many cases the values will be nearer 60 per cent or even less.

For the formation of a pound of steam from feed water under the general conditions that prevail in such engines, the heat required is about 1,100 B. t. u. It results that, with oil fuel, the heat obtained may be 10,000 to perhaps 13,000 B. t. u. per pound of oil burned, this heat producing 9 to 12 pounds of steam.

Under normal rates of operation and without forcing, each square foot of heating surface, if reasonably clean, will evaporate 2½ to 3½ pounds of steam; and thus a 40-horsepower boiler, with 400 square feet of heating surface, when working at its rated capacity, should produce about 1,200 pounds of steam per hour, with a consumption of 100 to 120 pounds of oil, or with a daily consumption of 7 to 9 barrels.

Similarly, with gas fuel and with the boiler working at about the normal rate and with efficiencies of the same order, the utilization of 500 to 700 B. t. u. per cubic foot of gas burned may be expected, and thus, for the same rate of operation as above, a 40-horsepower boiler would consume about 2,000 cubic feet of gas per hour or, roughly, 50,000 cubic feet a day.

Similarly, with wood fuel and the same order of boiler efficiency, a 40-horsepower boiler would consume, roughly, one-sixth to one-eighth of a cord per hour, or 3 to 4 cords a day.

At a rate of output considerably below the normal rating—as, for example, running a pump with a boiler suitable for a drilling rig—the efficiency will be considerably less than for normal conditions, and the cost of power per unit will be correspondingly greater. It can not be expected that a shell boiler, operated at one-quarter load or less, and under the conditions likely to prevail in the oil fields, will show an economy much above 50 per cent, and the economy may fall even below this value.

The following table, compiled by F. H. Oliphant, gives the average volumes of natural gas required to operate a gas engine or to supply a steam-engine plant using gas as fuel under boilers.

Volume of natural gas required for operating gas engines and gas-fired steam engines.

	Cubic feet per indicated horsepower hour.
Large gas engine, highest type	9
Ordinary gas engine	13
Triple-expansion condensing steam engine	16
Double-expansion condensing steam engine	20
Single-cylinder steam engine with cut-off	40
Ordinary high-pressure steam engine without cut-off	80
Steam engine ordinarily used for pumping oil wells	130

QUALITY OF FEED WATER.

In most of the oil fields of California the feed water available contains salts that are precipitated in the boiler, forming scale. The loss of heat from such incrustation increases, in a general way, with the thickness of the scale, although the structure of the scale, the manner in which it attaches to the iron, and the presence or absence of oil deposits with the scale are factors of equal or greater importance than thickness alone.

In general, the scale-forming constituents comprise the sulphates and carbonates of lime and magnesium, the oxides of iron, alumina, and magnesium, and earthy and organic matter. In addition, the water contains other salts that do not form scale under normal boiler conditions. These salts may include sodium, calcium, and magnesium chlorides, and the sulphates of sodium and potassium.

Carbonate of lime, calcium carbonate ($CaCO_3$), is practically insoluble in water, whereas bicarbonate of lime (Ca_2O_5) is decidedly soluble, and is of common occurrence in ordinary surface water. If the water be heated to 200° F., the bicarbonate is broken up by the carbon monoxide (CO_2) separating; and the resulting carbonate of lime being now insoluble, it separates as a somewhat powdery deposit. If the carbonate is mixed with other salts, however, especially sulphate of lime ($CaSO_4$), or if there is a little free sulphuric acid in the water, it may collect on the heating surfaces and form a hard, tough, and closely adhering scale. Bicarbonate of magnesium, magnesium bicarbonate ($MgCO_3$), is in a similar manner reduced to the simple carbonate, which is insoluble, and is deposited in the same fashion.

Calcium and magnesium sulphates are slightly soluble in cold water, but as the water is heated the proportion that can be held in solution becomes less and less and at the temperature of steam at about 100 pounds pressure these sulphates are practically all deposited. They collect on the heating surfaces and form, either with or without the carbonates, a hard, dense, closely adherent scale, and if they are allowed to accumulate to any considerable thickness, such as one-eighth to one-fourth of an inch, serious heat losses will result.

A typical analysis of water from the Coalinga field shows the following results:

Typical analysis of water from Coalinga field.

	Grains per gallon.
Calcium carbonate	5. 25
Magnesium carbonate	3. 61
Calcium sulphate	9. 62
Magnesium sulphate	8. 22
Silica and oxides of Fe and Al	3. 50
Alkali carbonate	None.
Alkali sulphate	45. 72
Alkali chlorides	6. 72
Incrustating solids	30. 20
Nonincrustating solids	52. 44
Total solids	82. 64

An analysis of scale formed from such water is as follows:

Analysis of scale formed from Coalinga water.

	Per cent.
Calcium carbonate	0. 06
Calcium sulphate	66. 40
Magnesium oxide	7. 60
Silica	1. 10
Oxides of Fe and Al	7. 70
Nonincrustating solids	10. 44
Water and organic matter	6. 70
	100. 00

In this case, for some accidental reason, the calcium carbonate content is low and the sulphate content high. The scale is practically a sulphate scale with a small admixture of other substances. The carbonate commonly is a more important constituent than in this instance.

The two general methods of dealing with boiler scale are (1) treating the feed water outside the boiler, and (2) treating the water within the boiler. Only the briefest reference can be made to the details of these methods. On the whole, treating the feed water outside the boiler is much to be preferred. It comprises in general the treatment of the water in some form of heater, usually with certain chemicals, soda ash, lime, etc., and under conditions approximating those in the boiler, at least to such a degree as to cause the precipitation in the heater of the solids that would otherwise be thrown down within the boiler. The heater being made in such form as to admit ready cleaning, the scale is deposited at a place where it does no harm and may be removed as conditions require.

Treatment of the water within the boiler requires a careful analysis of the water used for boiler feed, and the preparation by a suitable formula of some combination of chemicals which will either transform the substances insoluble in hot water into soluble substances or else cause their precipitation in a harmless, nonincrustating, powdery form that may be blown out periodically from the bottom of the boiler as mud or sludge.

Following are results of the use of open heaters with the waters of the Coalinga field. Soda ash was employed at the rate of about 4 ounces per horsepower of boilers per day.

RESULTS OF ANALYSIS OF WATER BEFORE TREATMENT.

	Grains per gallon.
Incrustating solids	19.94
Nonincrustating solids	58.21
Total solids	78.15

RESULTS OF ANALYSIS OF WATER AFTER TREATMENT.

Incrustating solids	4.17
Nonincrustating solids	82.69
Total solids	86.86

The temperature within the heater should be not less than 200° F., and the soda ash should be present in slight excess of the percentage barely necessary for the chemical reaction.

In order to give sufficient capacity for the treatment of the worst waters that may have to be used, the rated capacity of the heater may well be 40 or 50 per cent more than the rated power of the boilers. With this allowance the cost of reliable heaters installed and ready for operation will be not far from $8 or $9 per boiler horsepower. This investment, although seemingly large, will soon pay for itself in localities where the water carries as much scale-forming matter as do the waters of the Coalinga field.

RELATIVE IMPORTANCE OF DIFFERENT SOURCES OF POWER.

Although the present paper relates mainly to the operation of recovering oil, it is desirable to consider other uses of power at an oil property before deciding on the kind of power to be employed or the type of drive for pumping. Table 4 following shows the relative importance of the different methods of generating and utilizing power for pumping in the California oil fields.

TABLE 4.—*Means of generating and distributing power for pumping oil in the California oil fields during November, 1913.*

Field.	Steam.		Electricity.		Gas engines.		Compressed air.	Flowing.	Total wells.
	Beams.	Jacks.	Beams.	Jacks.	Beams.	Jacks.			
Coalinga	335	13	66		487	10			911
Lost Hills	45		5		21			31	102
McKittrick[a]	150	19	14		90	8	30		311
Midway	217		350		200		50	100	917
Sunset	181	10			40		25	[b] 50	306
Kern River	790	255	96	300	12	154	92		1,699
Santa Maria	94	9			130			[b] 7	240
Summerland		122							122
Santa Paula	5				30	295			330
Newhall					7	69			76
Salt Lake	60		25		155		[c] 50		290
Los Angeles		27		10		383			420
Whittier-Coyote	66	32	3			29		12	142
Puente	4	20				30			54
Fullerton	148	29			45	64		17	303
Total	2,095	536	559	310	1,217	1,042	247	217	6,223

[a] Includes Belridge.
[b] Includes wells in which agitators are used.
[c] Compressed air used in steam engines in place of steam.

STEAM ENGINES.

Although electric motors are being used with some success for drilling in shallow territory, and gas engines can be used for redrilling, it seems safe to predict that independent of other forms of power drive the use of the steam engine will still be required in the oil fields. No other form of prime mover seems to be so well adapted to the peculiar service required in the operation of drilling with standard tools. The steam engine has more elasticity and can remain stationary and maintain its maximum pull, a condition often required in cable drilling.

The type of engine commonly employed for drilling and frequently retained for the subsequent operation of the oil pump is the plain slide-valve, horizontal, single-cylinder, noncondensing engine. The most common size is 23 horsepower, with a cylinder 10½ by 12 inches and weighing about 4,000 pounds complete. Such an engine, which will supply the power required to operate a standard string of drilling tools, will be greatly oversize for pumping. It is nevertheless often allowed to remain and supply power for pumpimg at a greatly reduced rate of output.

The lifting of 100 barrels of oil a day from a well 1,000 feet deep will represent the continuous expenditure of only about 0.7 horsepower. This expenditure represents ideal conditions and includes no allowance for leakage, friction, viscous drag, and other secondary losses. The actual total work, of course, varies widely with the depth of well, condition of the oil, mechanical condition of the pump, intermediate mechanism, and engine. After all secondary losses have been accounted for, the actual expenditure of power may be three or four times that indicated by the mere gravity lift of the oil.

It results that the actual power required per well may range from 2 or 3 to 5 or 6 horsepower, depending on circumstances.

The economy of steam engines of the type mentioned depends on the initial steam pressure at the engine, the quality of the steam at the engine, and the load.

Under the best conditions practicable for such an engine—that is, assuming that the engine is in good condition, that it has a steam pressure of 100 to 125 pounds, that the steam is dry, and that there is full load—a horsepower-hour for 30 to 40 pounds of steam may be expected. With only one-fourth or one-fifth of full load and all other conditions the same, the consumption may be expected to rise to nearly twice these figures, or to 50 or 60 pounds. With leaky valves and poor general mechanical condition of the engine, and with wet steam at the end of a long, imperfectly protected steam pipe, the consumption may rise without limit, but easily to 75 or 100 pounds per horsepower-hour. Under such conditions the overall fuel consumption for the engine may vary from 3 to perhaps 10 pounds of oil per horsepower-hour.

When such an engine is used for pumping, the consumption will range toward the higher figures, and a daily consumption of 3 to 4 barrels for pumping alone may be expected, or for the average power demand on a producing property, including pumping, redrilling, and cleaning, an average consumption approximating 5 barrels a day.

The cost of the fuel component of power per horsepower-hour will vary with the prevailing rates for oil. These vary with market conditions and are at times controlled by factors other than supply and demand. The members of the Independent Producers Agency received about 38 cents per barrel during 1912. Some companies that made contracts during times of high prices still receive as high as 60 cents per barrel, whereas others, which contracted during the depression of 1905, are receiving as low as 15 cents per barrel. For the purpose of estimating, it may be assumed that at present the value of oil in the State ranges between 30 and 50 cents per barrel at the well, the latter figure being considered a high price. Under present prevailing conditions, about 8 per cent of the total production of the State (640,000 barrels per month) is used as fuel in the various fields.

STEAM PIPING.

The over-all economy and effectiveness of steam-power drive is vitally dependent on the design and the character of the installation of the steam piping. In the Kern River field, 42 wells are pumped with engines operated by steam from one central steam plant. Under such conditions the need of careful design and of proper construction becomes evident.

Within the limits of this paper complete rules for design can not be given. As a general guide, however, the cross-sectional area of the steam pipe may be made about one-fifteenth the area of the piston of the engine to be driven. For short steam lines—50 to 100 feet long—this area will insure the delivery of nearly full-boiler pressure at the engine. If a reduced pressure at the engine may be permitted, a correspondingly smaller size of pipe may be employed. For long lines, as in the distribution to a large number of wells, the pipe sizes must be increased to allow for increased length and for carrying condensation; otherwise there will be serious loss of pressure at distant points. In a network of distribution, the sizes must be graded for the volume of steam each is to carry or the number of engines it is intended to serve. The size of the pipe must be proportioned to the maximum demand that is liable to arise and will naturally be in excess of average demands.

Steam pipes should be insulated. If they are carried in the air, they should be surrounded with some nonconducting covering. A moderate investment in such material will soon pay for itself in steam saved. Pipes that are carried in the ground are in many places simply covered with oil sand. A rough wooden box filled with some form of standard nonconducting covering would, however, prove more effective in reducing heat losses and resulting condensation.

Special attention should be paid to so grading the pipe to slope that the condensed steam may be gathered at definite points and removed by steam traps or drains. As far as practicable, the pipes should slope back toward the boiler, thus permitting the condensation to be removed and readily used over again as feed water.

In long runs, allowance must be made for expansion and contraction from changes of temperature. For steam under a pressure of about 100 pounds the expansion and contraction per 100 feet of length may reach 2 inches. This contraction or expansion must be provided for by expansion joints or by such right-angle turns with freedom of movement as will permit the necessary come and go of the pipes. It is well to anchor the pipe at special points so as to compel the expansion and contraction to be taken care of at the points and by the means provided.

INTERNAL-COMBUSTION ENGINES.

Internal-combustion engines for use in the oil fields naturally will be of such type and design as will best suit the grades of fuel most directly available. The available fuels are natural gas, producer gas, and fuel or crude oil, to which may perhaps be added gasoline and engine distillate for use in case of emergency.

USE OF NATURAL GAS.

Natural gas consists chiefly of methane with small admixtures of heavier members of the marsh-gas and olefiant-gas series. Its heating value is not far from 1,000 B. t. u. per cubic foot. Natural gas, if properly diluted with air, makes an admirable fuel for the internal-combustion engine. Practically all the fields of the State yield natural gas. It is utilized extensively in Coalinga, where over 500 wells are operated with gas engines, and it is almost exclusively used in the Los Angeles City district, where pumping jacks driven by a gas engine operate 10 to 20 wells simultaneously. At some wells the flow of gas is not sufficient to warrant the erection of gas engines, and at others the uncertainty of a sufficient supply may render the use of fuel oil preferable. Some gas wells in the Buena Vista Hills, Midway district, yield great volumes of gas under heavy pressure, the product being piped to Los Angeles and neighboring towns for domestic purposes and sold to the oil companies in the Midway field.

At different wells the flow of gas with the oil varies within wide limits; measurements of 73 pumping oil wells in the Kern River field, situated on one property, gave volumes of 6,000 to 25,000 cubic feet per well a day, with an average pressure of 4 inches of water. This field is probably representative of fields having pumping wells.

UTILIZATION OF PRODUCER GAS.

Producer gas, made from coal of varying compositions, has been employed for a number of years in the operation of gas engines, and, more recently, successful types of apparatus have been developed for making such gas direct from crude oil. With the improvements that further experience may naturally develop in such apparatus, the oil producer-gas plant may be expected to become a means of generating gas for internal-combustion engines, and especially of utilizing those heavy oils that are now either sold at low prices or allowed to go to waste. Producer gas made in such apparatus has a heating value of not far from 200 B. t. u. per cubic foot, although the heating value may be varied within certain limits.

EFFICIENCIES OBTAINED WITH NATURAL GAS AND PRODUCER GAS.

The thermal efficiency of gas engines of the size and character available for use in the oil fields, if in good condition, will range from 20 to 30 per cent. Such engines will require 8.5 to 13 cubic feet of natural gas per horsepower-hour, and the fuel cost per unit of delivered power may be estimated on this general basis.

At certain wells 2,700 feet deep the engines are 30-horsepower, four-cycle type. The hourly consumption of natural gas is about 4,000 cubic feet when the engines are pumping at about 160 revolutions per minute.

For oil-producer gas, with its lower heating value, 40 to 60 cubic feet will be required per horsepower-hour, and the yield of gas per pound of oil will usually range from 50 to 70 cubic feet.

USE OF CRUDE OIL AND HEAVY FUEL OIL.

In recent years marked progress has been made in the direct use of crude and heavy fuel oils in internal-combustion engines, the engines best suited for using such fuel being of the Diesel type, in which very high compression is used, and the fuel is injected as a liquid into the compression space containing the air necessary for combustion. The fuel is there raised to the temperature of ignition by the high pressure at the end of the compression stroke.

It is generally admitted that the ideal fuel for this type of engine is a relatively light oil with a paraffin base and having a specific gravity of perhaps 0.9032 to 0.8750 (25° to 30° B.). Nevertheless, through the continued development of these engines seemingly satisfactory results have been had with much heavier oils, some having a specific gravity as low as 0.9523 or 0.9459 (17° or 18° B.); and more recent improvements have indicated the possibility of satisfactory operation with asphaltum as well as paraffin-base oils. Recent specifications for fuel for certain types of Diesel engine are as follows:

> Crude petroleum or fuel oil, either paraffin or asphaltum base, not heavier than 18° Baumé scale, free from acid, solid, or noncombustible matter, and containing not more than one-half of 1 per cent of sulphur or water.

The thermal economy of the Diesel type of engine is high, ranging between 25 and 35 per cent for loads varying from 50 per cent fuel load to 25 per cent overload. Such economy gives 12 to 18 brake horsepower per gallon of oil, and if the oil be taken as worth 40 cents per barrel in the field, the fuel item in the cost of power is reduced to 0.065 to 0.085 cent per horsepower-hour, or to 6.5 to 8.5 cents per 100 horsepower-hours. These results, however, require the best mechanical and operating conditions, and neglect or failure to realize such conditions will increase the consumption of fuel and the cost of power.

The Diesel type of engine has at present one limitation with regard to its general introduction as a prime mover. It is not as yet economically made in small sizes, and to obtain the best results units of 100 horsepower or more are desirable. It is, therefore, more suitable as a prime mover for a central power station than for the power demand at a single well.

For the development of electric power, the fuel consumption and value of fuel in the field being as noted above and the electric generator efficiencies being normal, the fuel item in the cost of electric power will vary from 0.10 to 0.135 cent per kilowatt-hour, or 10 to 13.5 cents per 100 kilowatt-hours. On the basis of these figures, the total cost of electric current produced by this engine, in moderate-sized units, will range slightly under 1 cent per kilowatt-hour, or about two-thirds of the present average cost of electrical power now delivered in the oil fields, assuming an annual power output equal to one-half of the full-rated capacity of the engine, including the cost of attendance and supplies and allowing 10 per cent for maintenance and depreciation, 6 per cent for interest, and 3 per cent for taxes and insurance. The last three items would apply against the cost of the electrical equipment and suitable building, as well as the engine and its equipment.

The price of engines of this type, although high, is not prohibitive, varying from $60 to $90 per horsepower. No central power station installation, therefore, should be made without investigating carefully the availability of the Diesel type of engine using crude or fuel oil.

The reasons for the small use of those engines in California are, in varying combinations, as follows: (1) The relatively high first cost; (2) the relatively complicated character of the engine as a whole and consequent liability to derangement, need of skilled attendance, and possible high cost of maintenance; (3) the disinclination of builders, until recently, to guarantee satisfactory operation with oils having an asphaltum base, and the relative scarcity and high price of oils with a paraffin base; (4) the lack of interest shown by users in matters pertaining to power-plant economics, this attitude being more marked in the exploitation of oil deposits in which it is assumed that small savings can be disregarded; (5) the low cost of crude oil, which reduces the actual saving resulting from the high fuel economy of the engines, a saving that in only few cases compensates for the high initial cost of the engines.

Irving C. Allen, chemist of the Bureau of Mines, who has studied the more effective means of utilizing heavy asphaltum oils, sums up his investigations in regard to the present status of the heavy-oil engines as follows: [a]

> The heavy-oil engine can not yet be considered as fully developed, and much work remains to be done in perfecting it. With the present imperfect knowledge of what the engine is capable of doing, and of what particular oils can be successfully used in it, one can not speak conclusively as to definite specifications for fuels and for lubricants, and those outlined above must be considered, therefore, as tentative.
>
> But the fact that petroleums containing as high as 20 per cent asphaltum, as well as oils from tars, have been successfully used is most encouraging. The future of the engine, and also a more efficient utilization for asphaltum liquid fuels and coal and wood by-product liquid fuels, is assured.

USE OF GASOLINE AND ENGINE DISTILLATE.

For the world at large, gasoline and engine distillate are perhaps the best known and most commonly used fuels for small internal-combustion engines. Their relatively high price, as refined products, however, tends to limit their use where the cost of power is a factor of importance. In the oil fields, therefore, these fuels are not used except in case of emergency or in default of others less expensive.

With gasoline fuel, small engines suitable for pumping will develop, according to conditions, from 6 to 10 brake horsepower-hours per gallon of fuel, and the fuel cost per unit of delivered power will vary from 1½ to 2 cents, according to the economy of the engine and the price of the fuel.

Engine distillate, a refined product representing a somewhat wider cut than gasoline and containing a small proportion of readily volatilized constituents together with others relatively heavier, is sold at prices approximating one-half those of gasoline. With a suitable form of carburetor, such fuel is readily employed in any engine built for gasoline, especially if gasoline be used for starting in case of shutdown. The economy in terms of brake horsepower-hours per gallon of fuel, will average about the same as for gasoline, and the fuel cost per unit of delivered power will, therefore, be about one-half that for gasoline fuel, or 0.75 to 1 cent per horsepower-hour.

ELECTRIC MOTORS.

For steady pumping under normal conditions the power for electric motors for direct pump drive of oil wells should usually average 3 to 5 horsepower. For very deep wells or for special conditions 6 or 8 horsepower may be needed.

The usual pumping speed is about 20 strokes per minute, but, owing to the need of increasing the speed when shaking up the oil, as high as 30 strokes per minute may be necessary. For cleaning the well, as compared with normal pumping, about double the speed and from three to four times the power is required.

---

[a] Allen, I. C., Heavy oil as fuel for internal-combustion engines: Technical Paper 37, Bureau of Mines, 1913, p. 26.

In the oil fields as a whole three or four kinds of electric motors are in use, all of the alternating-current, induction type.

THE SINGLE-SPEED MOTOR.

The single-speed motor, with the standard squirrel-cage rotor, may be first considered. This motor operates at one speed only and its highest efficiency is reached when it has nearly a full normal load. In common with motors of all types, the current density may, for a short time, be increased somewhat beyond the safe value for continuous service, and thus the short-time (one-half hour for example) power capacity of the motor may be correspondingly increased over normal rating.

Changes in speed and power may be obtained with this motor by introducing one or more of three special features, as follows:

(*a*) By suitable connections on the frame of the motor, the magnetic poles may be combined in groups of two, or used singly, as in the standard type. In this way the motor may be made to operate with the full number of poles or with half that number. The latter arrangement will result in doubling the speed. In this way a speed ratio of 2 to 1 is realized, and with the same torque, a 2-to-1 ratio for power.

(*b*) By using a wound rotor instead of the squirrel-cage construction, and bringing current to the rotor through slip rings, it becomes possible, by introducing a variable resistance into the rotor circuit, to realize a close step-by-step speed variation covering the range of, say, 50 per cent to full speed, there being corresponding changes in power.

(*c*) By making the field connections in such manner that the coils can be thrown into either a delta or Y connection, the power of the motor at the same speed and under the same general current density will be increased for the delta connection to a value about 1.7 times its value for the Y connection. Furthermore, by suitable design as to current capacity of coils and conductors, the current density may be increased readily in the ratio of 1.732 to 1 or even 2 to 1. This arrangement will assure a total power change in the ratio of 3 or more to 1. Thus with the Y connection the motor may be designed to operate with high efficiency on a steady pumping load of 4 to 7 horsepower, and then, by a throw of the switch, it becomes capable of carrying 20 to 25 horsepower with good efficiency for such period as may be required.

The use of special feature *a* alone gives the double-rated, two-speed motor. The combination of *a* and *b* gives the double-rated, two-speed, variable-speed motor. The use of *b* and *c* in combination gives the double-rated, single-speed, variable-speed motor.

The single-speed motor is suitable only for conditions permitting a constant speed and a nearly uniform power output. Such conditions are found in driving a number of jacks or in pumping an old well at a single speed and without cleaning. The principal use of such motors is for the driving of pumping jacks.

THE DOUBLE-SPEED MOTOR.

The double-speed motor *a* has the inherent simplicity and reliability of the single-speed type, with the added feature of two practically constant economic speeds in the ratio of 2 to 1. It has no slip rings that may spark and ignite escaping gases, and its first cost is somewhat lower than that of variable-speed motors.

On the other hand, the speed of operation, as for pumping, does not admit of close step-wise change. The motor has two speeds in the ratio of 2 to 1, and to obtain any other variation in the speed of the pump or other driven machinery such mechanical means as pulleys or gears must be used. These motors have been found to give effective service at old wells where one fixed speed can be used for pumping and another (the double) for cleaning.

THE VARIABLE-SPEED MOTOR.

The variable-speed motors *a* combined with *b*, and *b* combined with *c*, as noted, require slip rings; and these, if not in good mechanical condition, may cause sparking and resulting danger of fire in case gas escapes about the well. With proper housing and protection, however, this feature has not been found serious. The first cost of such motors is of course somewhat more than that of single or double speed motors. The great advantage of such motors is the graduated change of speed obtainable through the variable external resistance, and in the power change, either through the delta or Y line connection *c*, or through the pole-changing device *a*. As previously stated they are the only motors that can be considered as fairly meeting the various requirements of well-pumping service.

As between the two combination motors, the two-speed variable-speed motor *a* combined with *b* has the advantages of power variation over a range of 3 or 4 to 1, and of a speed variation of 40 to 50 per cent from two-base speeds, whereas the motor *b* combined with *c* has the same general advantage of power variation, but gives speed variation from one-base speed only. With the latter motor a pulley change is required in order to obtain double speed for cleaning.

With the motor *a* combined with *b* no pulley change is required—all speed changes necessary are provided for in the construction of the motor. The speed change may be closely graduated from two-base speeds to cover the wide power range between pumping and cleaning. With such a motor the various power requirements at the well, once the drilling is completed, can be met effectively and reliably.

A typical motor of this type for wells 600 to 1,200 feet deep is rated at 7 horsepower for continuous pumping service. Ordinarily 3 to 5 horsepower will be required for a speed of 600 revolutions per minute, or enough to give about 20 strokes per minute. For cleaning or other special service, the switch is thrown over, when the motor will carry 20 horsepower at 1,200 revolutions per minute. For heavier work, motors of 10, 25, 30, and 50 horsepower are now being manufactured.

For speed reduction, the motors for most wells are belted to a countershaft and thence to a large pulley; or, if a steam engine is to be displaced, the crank shaft and wheels of the engine may be used for a countershaft.

COST OF PUMPING BY ELECTRIC POWER.

The actual expenditure of electric energy for pumping varies widely. The average used in 71 wells, each about 1,600 feet deep, over a period of time for which records were kept, was 70.6 kilowatt-hours a day, which, at 1½ cents a kilowatt-hour, made the daily cost for pumping per well a trifle over $1.05. The deepest well, 2,692 feet, used about 90 kilowatt-hours daily.

In another instance the average for two months for 8 wells varying in depth from 1,000 to 2,800 feet was 93 kilowatt-hours a day.[a] In another instance the average for 12 wells averaging 1,100 feet in depth, with oil of a specific gravity of 0.9622 (15.5° B.), was 71.5 kilowatt-hours a day.[a] The average for another group of 107 wells, averaging 800 feet in depth, with oil of a specific gravity of 0.9756 (13.5° B.), was 57 kilowatt-hours a day.[a] In another instance, with 58 wells pumped by three motor-driven jacks, the average per well a day was 26.2 kilowatt-hours.[a] For another group of some 220 wells operated by jacks, the cost of electric energy per well per month varied from $6 to $14.40.[a]

Electric power in the field is sold at varying prices, the common figure being about 1.5 cents per kilowatt-hour.

USE OF MOTORS FOR ROTARY PUMPS.

Aside from use in well pumping, electric motors are also used for driving rotary pumps for sump holes, pipe lines, etc., the pumps being directly connected with the motor. These pumps are balanced at all pressures and are built for pressures up to 2,000 pounds per square inch.

---

[a] Gassaway, S. G., Cost of pumping oil by electricity: Western Engineering, October, 1913, p. 8, figures furnished by S. G. Gassaway.

AIR-LIFT PUMPING PLANTS.

STEAM-DRIVEN COMPRESSORS.

The most complete compressor plants in the oil fields are in the Kern River field, one company having three high-duty compressor plants, installed at an expense of about $200,000. The largest one of these has a free-air capacity of 4,000 cubic feet and the other two 2,000 cubic feet each. The compressors used in the largest plant are two 2,000-cubic foot steam-driven machines with cross-compound condensing Corliss steam cylinders and twin-tandem, two-stage air cylinders. The two steam cylinders are 17 and 36 inches in diameter; the four air cylinders are in pairs, one pair being 9½ inches and the other 19½ inches diameter, all with a common stroke of 36 inches. The normal full-load speed is 80 revolutions per minute and each engine develops 650 horsepower. The initial steam pressure is 150 pounds, which, with a 26 to 28 inch vacuum, compresses the air to a pressure of 200 pounds for delivery to the service mains.

The boiler equipment includes five 207-horsepower watertube boilers, each with a working pressure of 160 pounds. Three of the boilers are in constant use, and generate sufficient steam for the operation of the entire plant, including all auxiliaries and a 75-kilowatt lighting set. The cooling tower reduces the temperature of the condenser circulating water from 110° F. to 78° F. The cost of the cooling tower was $900.

GAS-ENGINE COMPRESSORS.

The wells of one oil-well company yield enough natural gas to run a 2,600-cubic foot compressor plant, and, as natural gas is practically a waste product, it is not charged against the cost of operation, so that the cost of each horsepower developed is very low.

The compressors are of the same make and type as those of the company just previously mentioned, except that they are coupled directly to gas engines. One compressor has air cylinders 11 and 22 inches in diameter, with a 24-inch stroke, and a rated capacity, at 150 revolutions per minute, of 1,600 cubic feet of free air per minute, compressed to a pressure of 200 pounds per square inch.

The compressor moving parts are coupled directly to the crank shaft of a Buckeye, two-cylinder, horizontal, double-acting tandem, four-cycle, natural-gas engine, having cylinders 18 inches in diameter, with a stroke of 24 inches. The other compressor has a rated capacity, at 150 revolutions per minute, of 1,000 cubic feet of free air per minute, compressed to a pressure of 200 pounds, and is coupled to a single-cylinder Buckeye engine of the same type as that operating the larger compressor, the cylinder being 18 inches diameter with a stroke of 30 inches.

The larger engine has a brake-horsepower capacity of about 450 and the smaller of about 320. The maximum power developed under ordinary working conditions is about 360 and 280 horsepower for the larger and smaller engines, respectively, the air pressure shown on the gage being 190 pounds.

The figures for cost of power per horsepower developed, based on averages of about a year and a half of continuous operation, are given in the comparison of costs of different methods.

OPERATION OF THE PLUNGER PUMP.

A total of 5,809 wells, or about 93.3 per cent of the total number in California, are operated with the plunger pump. This type of pump is commonly driven by connection from the walking beam, which receives its motion from a connecting rod attached to the crank of the sand-reel shaft, or by a jack operated through a jerker line from a pumping "power," the pumping power and the sand-reel shaft being driven directly by belt or gear connection from the source of power. The source may be a steam engine, a gas engine, an electric motor, or even a windmill. The operation of the plunger pump with the walking beam is greatly facilitated by the use of the tail pump (fig. 6), which drives from the weight of the sucker rods in the well. The tail pump is employed to handle the oil from the sump, whence it is discharged into the storage or delivery tanks.

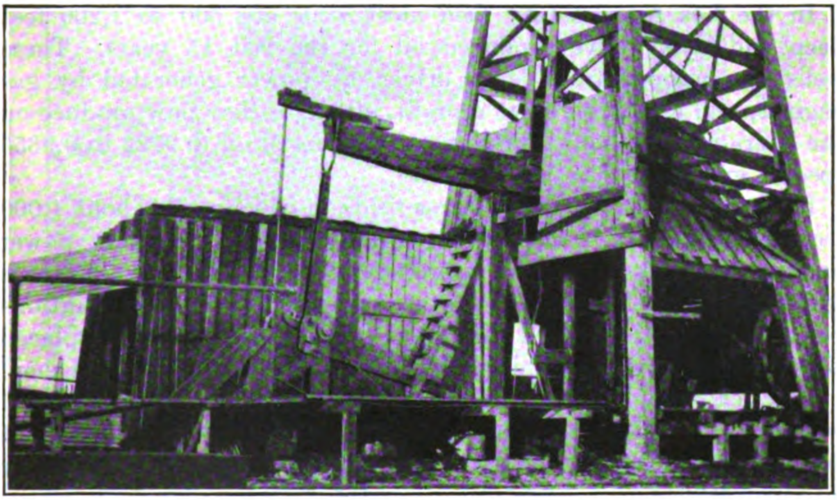

FIGURE 6.—Typical construction of pumping well operated with walking beam. Tail-pump device is shown.

If the wells are of moderate depth, produce little or no sand, and are not too widely scattered, the pumps may be driven as a group by a

Original from PRINCETON UNIVERSITY

pumping "power." This device consists of a vertical rotating shaft, having one or more eccentric disks from which radiate the jerker lines, which transmit the pull to the pump rods by means of a frame or jack placed over the well. In order to obtain the best results, it is necessary that the pumping power be so placed in regard to the wells or counterbalanced in such manner that the pull from opposite directions is about equal. If the ground is fairly level, and the wells are not more than 600 to 700 feet apart, it is claimed that as many as 40 to 50 wells can be pumped economically with jerker lines; but in common practice not over 25 wells are pumped with one unit, thus reducing the number that would become unproductive if the pumping power should fail. The wells should not be so far from the power that the elongation of the jerker lines when pulled would neutralize most of the motion.

In the Los Angeles City field most wells are 500 to 1,200 feet deep and many have produced oil for the last 15 years. These wells are pumped from jacks driven by power generated by gas engines, and are operated at a profit, although they now produce on the average only about four-fifths of a barrel of oil (0.9722 to 0.9655 specific gravity, 14° to 19° B.) daily.

In a property in the Kern River field, on which wells about 1,000 feet deep produce a heavy oil, a motor-driven pumping power operates 22 wells at a cost of approximately $6 a day. The power is driven by a 30-horsepower motor operating at 1,120 revolutions per minute. It is claimed that three of these outfits have displaced eight 70-horsepower boilers and reduced the labor from 35 to 21 men.

Practically all of the 122 wells in the Summerland field are pumped with jacks operated with steam engines (fig. 7). These wells are about 600 feet in depth and produce an average of about 1 barrel of heavy oil a day each.

WINDMILLS.

Although the windmill occupies a position of no economic importance as a prime mover for oil-well pumping, it is interesting to note that two or three of the wells of the Rosedale Cemetery Association were pumped by a windmill for some time.[a] These wells, located in the Salt Lake field, are from 60 to 160 feet deep. Moreover, the first well in the Oil City field in Coalinga, about 160 feet deep, was pumped by a windmill for some considerable period of time.

SWAB AND BAILER.

The swab and bailer, when employed, are operated from the sand-reel shaft exactly as in the use of the swab for removing drillings. The bailer is often used for the removal of sand when for one reason or another a new well may be backward in starting its flow and evidences of its sanding up are found. The swab also is employed under similar conditions, though its use should be governed by judgment. Neither the bailer nor the swab is used in California for the direct recovery of oil under normal operating conditions.

---

[a] Prutzman, P. W., Petroleum in southern California: Cal. State Mining Bureau Bull. 63, 1913, p. 232.

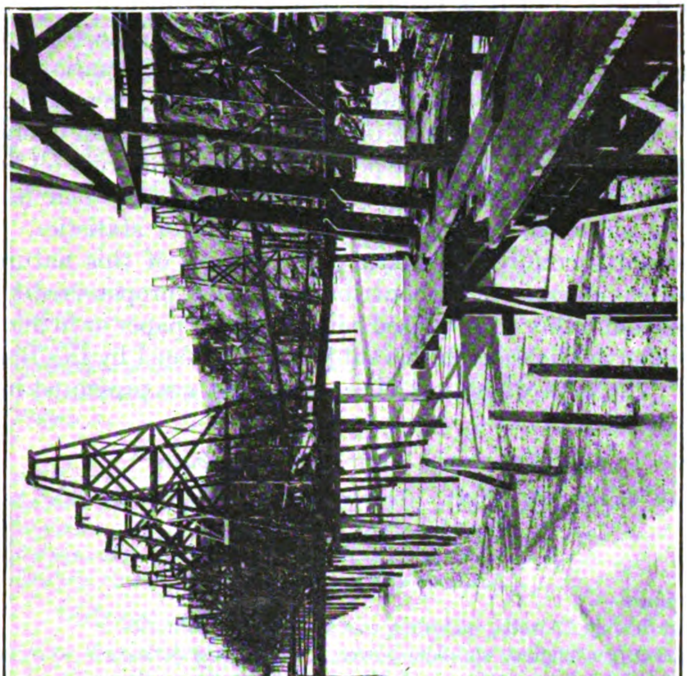

Figure 7.—Part of Summerland field showing wells on wharves, the wells being pumped by "powers." [Photograph by G. H. Eldridge, for U. S. Geological Survey.]

DATA AS TO COST OF DIFFERENT METHODS OF RECOVERING OIL.

Below are presented data regarding the cost of different methods of recovering oil and generating power. The figures apply only to specific instances, and it is evident that if used in calculating the cost of proposed plants the results obtained will, in most cases, be misleading. However, it is believed that the information given will be found of value as furnishing a general guide for any specific problem. The figures have been obtained largely from oil operators and represent results of actual experience in the California oil fields.

As the figures presented relate to specific instances, their usefulness will be enhanced by further complete sets of statistics. The authors would therefore appreciate contributions of this nature by oil and gas engineers. Such contributions, with proper credit, will be incorporated either in a revised edition of this paper or in another more extended publication on this subject to be issued by the Bureau of Mines. The data which have been collected are presented in the following table:

Data relative to cost of well-pumping equipment.

1. Depth of Wells 800− Feet. Gravity of Oil +0.875 (+15° B.). Santa Clara Valley District.

(Data by W. R. Hamilton.)

Initial Cost of Installation.

Pumping power—

Station driving 17 wells, including cost of building, 20-horsepower gas engine, simplex power, belt, piping, jerker lines, labor—everything up to the derricks at the wells, but not including pumping jacks at wells, tubing or rods	$3,068.36
Cost per well	180.49

Cost of Operation and Maintenance.

Pumping.—Cost, including wages of pumpers, all repairs and replacements for power plants and jack lines, lubricating oils, etc., but not including repairs to wells, depreciation of plants, or interest on investment, varied from 30 to 55 cents a day per well, depending on the extent of the replacements necessary. An average for a long period would be about 43 cents.

2. Depth of Wells 1,000± Feet. Gravity of Oil ±0.965 (±15° B.). Kern River Field.[a]

Cost of Operation and Maintenance.

Steam engines.—50.8 cents per barrel.

Air compressor.—2.4 cents per barrel.

Remarks.—The difference in cost is due to the increased production when compressed air is used.

3. Depth of Wells 1,000± Feet. Gravity of Oil ±0.965 (±15° B.). Kern River Field.[a]

Cost of Operation and Maintenance.

Steam engines.—20.24 cents per barrel.

Pumping power.—(Driven by electric motor) 18.28 cents per barrel.

Remarks.—The daily production per well was about 20 barrels.

---

[a] Data based on confidential information.

4. DEPTH OF WELLS 1,000± FEET. GRAVITY OF OIL ±0.965 (±15° B.). KERN RIVER FIELD.

(Data by C. T. Hutchinson.)

INITIAL COST AND COST OF INSTALLATION.

Air compressors.—Three plants, one with a capacity of 4,000 cubic feet of free air and two with a capacity of 2,000 cubic feet of air, $200,000.

Remarks.—The first plant comprised two compressors each with a capacity of 2,000 cubic feet of free air. Each compressor had a Corliss steam cylinder and twin-tandem air cylinders, and each machine required 650 horsepower when developing a pressure of about 150 pounds per square inch. There were five 207-horsepower water-tube boilers, one 75-kilowatt electric-light plant, and two condensers.

5. DEPTH OF WELLS 1,000± FEET. GRAVITY OF OIL 0.9722 (14° B.). KERN RIVER FIELD.

(Data by Kern River Oil Fields (Ltd.).

COST OF OPERATION AND MAINTENANCE.

Steam engines.[a]—	
Labor	$0.36
Repairs	.07
General expense	.03
Fuel oil (assuming price of 30 cents per barrel)	.90
Water	.50
	1.86
Electric motors.[a]—	
Labor	$0.29
Repairs	.07
General expense	.03
Electric current	.56
Daily cost per well	.95

6. DEPTH OF WELLS[b] 600 TO 1,200 FEET. GRAVITY OF OIL 0.9790 (13° B.). MIDWAY FIELD.

(Data by R. S. Hazeltine.)

INITIAL COST AND COST OF INSTALLATION.

Electric motors.—	
New roof on engine houses	$240.00
Eleven 15 to 5 horsepower motors, One 20 to 6 horsepower motor, Three 25-kilowatt transformers,	6,670.00
Installation	3,500.00
Counterbalance for beams	300.00
Discarded steam engines	1,000.00
Total	11,710.00
Cost per well	975.83

COST OF OPERATION AND MAINTENANCE.

Steam engines.—	
Labor	$409.50
Fuel oil	523.20
Water	697.00
Repairs to boilers and engines	88.44
Oil waste and packing	97.42
Total	1,815.56
Average daily cost per well	5.09

---

[a] Forty-eight wells.

[b] Twelve in group.

Electric motors—	
Labor	$432.70
Electric equipment	390.27
Fuel oil	156.20
Water	349.89
Repairs to boilers and engines	22.30
Oil waste and packing	62.54
Total	1,413.90
Average daily cost per well	3.85

Remarks.—Boiler water was purchased at 5 cents per barrel and oil produced was contracted at 50 cents per barrel.

7. DEPTH OF WELLS 900 TO 1,200 FEET. GRAVITY OF OIL 0.9655 (15° B.). KERN RIVER FIELD.

(Data by A. G. Crites.)

INITIAL COST AND COST OF INSTALLATION.

Steam engines—	
Corliss condensing engines, 320 and 420 horsepower	$69,050.93
Myers noncondensing cut-off engines	41,430.59
Electric motors—	
Electric driven plant, 420-horsepower	27,620.37
Gas engines—	
Included under air compressors.	
Air compressors—	
One 320-horsepower, driven by Buckeye gas engine pipe lines, etc., complete	39,344.19
One 420-horsepower, driven by Buckeye gas engine, complete	22,781.79

COST OF OPERATION AND MAINTENANCE.

Steam engines—	
Corliss—	
Interest for 1 year at 6 per cent	$4,143.05
Depreciation for 1 year at 10 per cent	6,905.09
Labor, 4 men at $100 per month	4,800.00
Repairs and incidentals (estimated)	1,800.00
Fuel oil, 23,005 barrels at 35 cents per barrel	8,051.75
Total for 1 year	25,699.89
Myers—	
Interest for 1 year at 6 per cent	2,485.83
Depreciation for 1 year at 10 per cent	4,143.05
Labor, 4 men at $90 per month	4,320.00
Repairs and incidentals (estimated)	1,000.00
Fuel oil, 51,500 barrels at 35 cents per barrel	18,025.00
Total for 1 year	29,973.88
Gas engines—	
Included under air compressors.	
Electric motors—	
Interest at 6 per cent	1,657.22
Depreciation at 10 per cent	2,762.03
Labor, 2 engines at $135 per month	3,240.00
Repairs and incidentals (estimated)	500.00
Power, 4,326,406 kw. at 1 cent per kw	43,264.06
Total for 1 year	51,423.31

Air compressors—	
One 320 horsepower—	
Interest for 10 months at 6 per cent	$1,967.21
Depreciation for 10 months at 10 per cent	3,278.68
Labor—	
One engineer, $150 per month	1,500.00
One engineer, $4.50 a day	1,363.50
Extra labor, repairs	82.00
Extra material for repairs	249.44
Oil, water, and incidentals	710.20
Total for 10 months	9,151.03

Remarks.—Natural gas is recovered by the vacuum made by the gas engines, its value not being considered therefore.

Cost of power per horsepower-hour was 0.00478 in 1910, 0.00488 in 1911, and 0.00260 in 1912.

8. DEPTH OF WELLS 1,850 TO 2,000 FEET. GRAVITY OF OIL ±0.952 (±17° B.). COALINGA FIELD.

(Data by Thomas Cox.)

INITIAL COST AND COST OF INSTALLATION.

Gas engines—	
Installation, gas mains, traps, tail pumps, foundations, engines proper, belting, and engine houses	$1,260

COST OF OPERATION AND MAINTENANCE.

Steam engines—	
Average total cost per well per month	$270
Average total cost per well per day	9
Gas engines—	
Three men per tour (12 hours) to 19 wells	33
Two repair men	21
Lubricating oil per well per month	6
Repairs, power, and attendance per well per month	60
Repairs, power, and attendance per well per day	2

Remarks.—Thirty and 45 horsepower engines. Five-inch water pressure. Magneto ignition.

9. DEPTH OF WELLS 1,600 TO 2,500 FEET. GRAVITY OF OIL 0.9589 (16° B.). COALINGA FIELD.

(Data by Thomas Crumpton.)

INITIAL COST AND COST OF INSTALLATION.

Steam engines—	
One 23-horsepower engine complete	$296.69
One 40-horsepower boiler	473.00
Boiler connections	116.15
Engine house, 12 by 14 feet, blocks, lumber, labor, etc	66.80
Total	952.64
Gas engines.—	
One 30-horsepower engine and connections	$1,027.04
Engine house, 16 by 14 feet, cement foundation, including labor	250.13
Total	1,277.17

Digitized by Google Original from PRINCETON UNIVERSITY

COST OF OPERATION AND MAINTENANCE.

Steam engines.—	
Operation:	
2 pumpers, at $105 a month, for five engines	$42.00
10 gallons of steam-engine oil, at 19 cents	1.90
14 gallons of cylinder oil, at 30 cents	4.20
180 barrels of fuel oil for boiler for well	90.00
Haulage of lubricating oil (labor and horse)	1.00
Maintenance:	
Labor and horse per month per well	3.10
Repairs of boilers per month per well	19.30
Average per well per month	161.50
Average per well per day	53.83
Gas engines.—	
Operation:	
2 pumpers, at $105 per month, for 11 engines	19.09
13 gallons of engine oil, at 44 cents	5.72
4 gallons of engine oil, at 23 cents	.92
Haulage of oil (labor and horse)	1.50
Maintenance:	
Labor and horses, at $275 per month, for 50 engines	5.50
Repairs and renewals, at $88.95, for 50 engines, per month	1.78
Average per well per month	34.51
Average per well per day	1.15

10. DEPTH OF WELLS, 2,745 FEET. GRAVITY OF OIL ±0.952 (±17° B.). COALINGA FIELD.

(Data by Thomas Cox.)

INITIAL COST AND COST OF INSTALLATION.

	Per cent.
Steam engines.—	
A. Individual steam plant for each two wells, using oil for fuel	100
Gas engines.—	
B. Individual 30-horsepower gas engines, four-cycle type, magneto ignition; including gas mains and accessories	195
Electric motors.—	
C. Motor at each well, necessary transmission lines, transformers, and receiving station; power purchased	100
D. Central plant with steam turbines, fired with fuel oil, motor at each well	196
E. Central plant with steam turbines, fired with natural gas, motor at each well	227
F. Central plant. Engine-type generators, driven directly by gas engine. Electric motor at each well	264
Air compressors.—	
G. Central plant. Air compressors directly connected to gas engines, using natural gas. Air distributed to each well for operating steam engines	388
H. Central plant. Steam-driven air compressors, boilers fired by natural gas. Air distributed to each well for operating steam engines	393
I. Central plant. Steam-driven air compressors, boilers fired with fuel oil. No gas lines. Air distributed to each well for operating steam engines	337

COST OF OPERATION AND MAINTENANCE.

		Per cent.
Steam engines.—		
Comparative working cost of operating equipment A		100
Cost of operating steam plants, based on 100-month wells, per well per month, one pumper per well:		
Labor attendance	$104.88	
Fuel oil	105.47	
Labor, scaling boilers	15.62	
Repairs, material	9.57	
Engine repairs	5.56	
Lubricating oils	7.73	
Boiler flues	4.00	
Water	17.17	
Per well per month	270.00	
Per well per day	9.00	
Gas engines.—		
Comparative working cost of operating equipment B		34
Pumping cost for 8 wells with two men in attendance per month:		
Labor, 2 men, at $3.50 per day	$210	
Lubricating oils, $7.50 per well	60	
One-quarter of 2 repairmen, at $8.50 a day	66	
Repairs and renewals	120	
8 wells, per month	456	
Per well per month	57	
Per well per day	1.90	
Electric motors.—		
Comparative working cost of operation:		
Equipment C		80
Equipment D		61
Equipment E		50
Equipment F		44
Air compressors.—		
Comparative working cost of operation:		
Equipment G		46
Equipment H		56
Equipment I		73

Remarks.—Percentage costs are based on investment for equipment necessary to operate 50 wells, pumping 100 barrels a day per well. Steam plants using fuel oil, and placed between each of two wells, with two-pump attendants to each two wells, are considered as unity for basis of comparison.

PUBLICATIONS ON PETROLEUM TECHNOLOGY.

A limited supply of the following Bureau of Mines publications is available for free distribution. Requests for all publications can not be granted, and applicants should limit their selection to publications that may be of especial interest to them. Requests for publications should be addressed to the Director, Bureau of Mines, Washington, D. C.:

BULLETIN 19. Physical and chemical properties of the petroleums of the San Joaquin Valley, Cal., by I. C. Allen and W. A. Jacobs, with a chapter on analyses of natural gas from the southern California oil fields, by G. A. Burrell. 1911. 60 pp., 2 pls., 10 figs.

BULLETIN 65. Oil and gas wells through workable coal beds; papers and discussions, by G. S. Rice, O. P. Hood, and others. 1913. 101 pp., 1 pl., 11 figs.

TECHNICAL PAPER 3. Specifications for the purchase of fuel oil for the Government, with directions for sampling oil and natural gas, by I. C. Allen. 1911. 13 pp.

TECHNICAL PAPER 10. Liquefied products from natural gas; their properties and uses, by I. C. Allen and G. A. Burrell. 1912. 23 pp.

TECHNICAL PAPER 25. Methods for the determination of water in petroleum and its products, by I. C. Allen and W. A. Jacobs. 1912. 13 pp., 2 figs.

TECHNICAL PAPER 26. Methods of determining the sulphur content of fuels, especially petroleum products, by I. C. Allen and I. W. Robertson. 1912. 13 pp., 1 fig.

TECHNICAL PAPER 32. The cementing process of excluding water from oil wells as practiced in California, by Ralph Arnold and V. R. Garfias. 1913. 12 pp., 1 fig.

TECHNICAL PAPER 36. The preparation of specifications for petroleum products, by I. C. Allen. 1913. 12 pp.

TECHNICAL PAPER 37. Heavy oil as fuel for internal-combustion engines, by I. C. Allen. 1913. 36 pp.

TECHNICAL PAPER 38. Wastes in the production and utilization of natural gas and means for their prevention, by Ralph Arnold and F. G. Clapp. 1913. 29 pp.

TECHNICAL PAPER 42. The prevention of waste of oil and gas from flowing wells in California, with a discussion of special methods used by J. A. Pollard, by Ralph Arnold and V. R. Garfias. 1913. 15 pp., 2 pls., 4 figs.

TECHNICAL PAPER 49. The flash point of oils; methods and apparatus for its determination, by I. C. Allen and A. S. Crossfield. 1913. 31 pp., 2 figs.

TECHNICAL PAPER 51. Possible causes of the decline of oil wells and suggested methods of prolonging yield, by L. G. Huntley. 1913. 32 pp., 9 figs.

TECHNICAL PAPER 53. Proposed regulations for the drilling of gas and oil wells, with comments thereon, by O. P. Hood and A. G. Heggem. 1913. 28 pp., 2 figs.

TECHNICAL PAPER 57. A preliminary report on the utilization of petroleum and natural gas in Wyoming, by W. R. Calvert, with a discussion of the suitability of natural gas for making gasoline, by G. A. Burrell. 1913. 23 pp.

TECHNICAL PAPER 66. Mud-laden fluid applied to well drilling, by J. A. Pollard and A. G. Heggem. 1914. 21 pp., 12 figs.

TECHNICAL PAPER 68. Drilling wells in Oklahoma by the mud-laden fluid method, by A. G. Heggem and J. A. Pollard. 1914. 27 pp., 5 figs.

INDEX.

A. Page.

Agitator string, figure showing 23
  use of 22, 23
Air compressor, cost of operating 48–53
Air lift, advantages of 14, 20
  air needed for 15, 20
  disadvantages of 21
  figure showing 18
  operation of, principles governing 14
  regulation of 15
  tests of 19
  tubing for, submergence of 16, 18, 19, 20
  theory of 18
  use of 14, 16
Air-lift plants, features of 44
Air supply for oil burners, need of controlling 27
Allen, I. C., on heavy-oil furnace 40
Atomization of oil fuel, cost of 26

B.

Bailer, operation of 46, 47
  size of 24
  use of 46, 47
Bailing oil wells, method of 24
Boiler water, treatment of 33
Burners for oil fuel, features of 26

C.

Casing, life of 10
  perforating of 9, 10
  steel, use of 10
  wrought-iron, use of 10
Crude oil, as fuel for internal-combustion engines 38
  See also Oil.
Coalinga fields, analysis of water from 32
  depth of pumping wells in 11
  generation and distribution of power in 34
  recovery of oil in 9, 11
    cost of 51–53
Compressed air, use of, in oil recovery 15
    conditions governing 15
    disadvantages of 21
  See also Air lift; Air compressor.
Cox, Thomas, acknowledgments to 5
Crites, A. J., acknowledgments to 5
Crumpton, T. J., acknowledgments to 5

D.

Davis, G. J., on submergence of tubing of air lift 18
Diesel engine, advantages of 39
  cost of producing power with 39
  efficiency of 38

Page.
Diesel engine, oil fuel for 38
  price of 39
Double-speed motor, features of 42
Durand, W. F., acknowledgments to 5

E.

Electric motors for pumping, double-speed, features of 42
  horsepower of 40
  operation of, cost of 43, 49–53
  reasons for use of 27
  single-speed, features of 41
  variable speed, features of 42
  uses of 43
Electric power for pumping, distribution of 27
Engine distillate, cost of generating power with 40
  definition of 40
  use of 40
Engine. *See* Diesel engine, gas engine, internal-combustion engine, steam engine.
Evangeline, La., cost of air-lift pumping at 19

F.

Feed water, analysis of 32
  scale-forming, salts in 31
    removal of 33
Fuel oil, amount of, consumed in steam boilers 30
  heavy, use of, in internal-combustion engines 38
Fullerton field, devices used in 11
  generation and distribution of power in 34
  production of oil in 11

G.

Gas engines, cost of operating 50–53
  efficiency of 38
Gasoline, use of, for internal-combustion engines 40
Gross production of oil. *See* "Oil recovered."

H.

Hamilton, W. R., acknowledgments to 5
Hazeltine, R. S., acknowledgments to 5
Heavy-oil furnace, development of 40
Hutchinson, C. T., acknowledgments to 5
  on air pressure of well in Kern River field 18

I.

Internal-combustion engine, fuels for 10, 37, 40
  using gas, efficiency of 31, 38
Ivens, E. M., on results of air-lift pumping 19

Digitized by Google Original from PRINCETON UNIVERSITY

K. Page.

- Kern River field, air-lift pumping in, 15
    - consumption of air in, 20
  - air-lift systems in, tests of, 19
  - compressor plants in, features of, 44
  - cost of recovering oil in, 48–51
  - generation and distribution of power in, 34
  - operation of air lift in, 18
  - production of oil in, 7, 11
  - recovery methods in, 11
  - waste of oil in, 7

L.

- Locomotive boiler, features of, 29
- Logs, well, need of, 10
- Los Angeles field, generation and distribution of power in, 34
  - method of pumping wells in, 46
  - oil recovery in, 11
  - production of oil in, 11
- Lost Hills field, generation and distribution of power in, 34
  - oil recovery in, 11
  - production of oil in, 11

M.

- McKittrick field, generation and distribution of power in, 34
  - oil recovery in, 11
  - production of oil in, 11
- Midway field, generation and distribution of power in, 34
  - oil recovery in, 11
    - cost of, 49, 50
  - production of oil in, 11

N.

- Naramore, Chester, acknowledgments to, 5
- Natural gas as source of gasoline, 27
  - combustion of, 28
  - composition of, 27, 37
  - construction of pipe lines for, 28
  - heating value of, 27
  - use of, as boiler fuel, 27, 28, 30, 31
    - in gas engines, 25, 31, 37
    - yield of, 37
- Newhall field, generation and distribution of power in, 34
  - production of oil in, 11
  - recovery of oil in, 11

O.

- "Oil content", definition of, 6
- Oil fuel, furnace control of combustion of, 26
  - heating value of, 25
    - factors controlling, 25
  - permissible water content of, 26
  - use of, for boilers, 25
  - waste of. *See* Waste.
- Oil mining by tunnels, 24
- Oil property, proven, definition of, 6
    - value of, 6
- Oil recovered, definition of, 6
  - losses in, 6, 7
  - ratio of, to "recoverable oil", 6
- Oil recovery, efficiency of, 8
- Oil wells. *See* Wells.
- Oliphant, F. H., on gas for operating gas engines, 31
- Orcutt, W. W., acknowledgments to, 5

P.

- Perforating machines, trouble from use of, 9, 10
- Petroleum. *See* Oil.
- Plunger pump, capacity of, 13
    - features affecting, 13
  - features of, 11
  - figure showing, 45
  - number of wells operated by, 45
  - operation of, 12, 45
  - use of, 21
  - working barrel of, figure showing, 12
- Power for pumping, amount required, 35
  - distribution of, 34
  - fuel for generation of, 25–28
    - cost of, 35, 39
  - source of, in oil fields, 25, 34
- Power stations, central, use of, 30
- Producer gas, heating value of, 38
  - use of, in internal-combustion engines, 37
- Proven oil property, definition of, 6
- Production of wells, factors controlling, 6
- Prutzman, P. W., on disadvantage of tunneling for oil, 24
- Puente field, generation and distribution of power in, 34
  - oil recovery in, 11
  - production of oil in, 11
- Pump. *See* Plunger pump.
- Pumping oil, choice of apparatus for, 8
  - cost of, 8
  - difficulties in, 8, 12
  - efficiency of, 8
  - electric power for, cost of, 43
  - operation of, details of, 14
  - *See also* Air lift.
- Pumping "power," details of, 46
- Pumps, types of, 11, 12

R.

- Records of oil wells, advisability of keeping, 10
- "Recoverable oil," definition of, 6
  - loss of, causes of, 7
  - ratio of, to "oil recovered", 6
- Rix, E. A., on test of air lift in Kern River field, 19

S.

- Salt Lake field, generation and distribution of power in, 34
  - oil recovery in, 11
    - method of, 22
  - production of oil in, 11
  - use of plunger pump in, 16
- San Joaquin Valley field, difficulties encountered in, 12
  - recovery of oil in, 8
- Sand, in oil in Sunset field, volume of, 23
  - in oil, amount of, 22, 26
    - harm caused by, 12, 26
    - removal of, by air lift, 20
- Santa Clara field, cost of recovering oil in, 48
  - oil properties in, efficiency of, 8

Page.

- Santa Maria field, difficulties encountered in.. 13
  - generation and distribution of power in. 34
  - oil recovery in 11
  - production of oil in 11
- Santa Paula field, generation and distribution of power in 34
  - oil recovery in 11
  - production of oil in 11
- Scale, boiler, analysis of 32
  - cause of 31
  - harm resulting from 32
  - methods of removing 33
- Screen for oil wells, use of, conditions governing 9
- Single-speed motor, method of changing power of 41
  - method of changing speed of 41
  - suitability of, conditions governing 42
- "Skimming," definition of 21
- Steam, utilization of, in oil recovery 22
- Steam boilers, efficiency of 30, 31
  - fuel consumption of 30
  - setting of 30
  - sizes used 29
  - types used 29
- Steam engine, advantages of, for drilling 34
  - cost of operating 48–53
  - economy of 35
  - fuel requirements of 35
  - fuel consumption of 35
    - cost of 35, 36
  - sizes of 34, 35
  - type used in drilling 34
  - use of 2
- Steam piping, construction of 36
  - insulation of 36
  - proper size of 36
- Sucker rod, average life of 12
- Summerland field, generation and distribution of power in 34
  - method of pumping wells in 46
  - oil recovery in 11
  - production of oil in 11
  - view of wells in 47
- Sunset field, generation and distribution of power in 34
  - oil recovery in 11
  - production of oil in 11

Page.

- Sunset field, sand from wells in 22
  - typical well in, figure showing 23
- Swab, operation of 24, 46, 47
  - use of 46, 47

T.

- Thompson, A. B., on removal of sand by air lift 20
- Tubing, average life of 10, 12
- Tunneling for oil, difficulties in 24
  - method of 24

V.

- Valves, pump, method of grinding 13
- Variable-speed motor, advantage of 42
  - features of 42

W.

- Waste of oil, causes of 6, 7
  - figure showing 7
  - percentages of 7
- Water, pumping of, from oil wells 17, 18
- Water in oil, percentage of 26
- Water. *See also* Feed water.
- Water-bearing beds, occurrence of, in oil property 6
- Weidner, C. R., on formula for air-pump lifting 18
- Wells, conditions affecting yield of 9
  - cost of pumping 8
  - logs of, value of 10
  - pumping, method of operating 14
- Whittier-Coyote field, generation and distribution of power in 34
  - oil recovery in 11
  - production of oil in 11
- Williams, W. A., acknowledgments to 5
- Windmills, for oil-well pumping 46
- Wood fuel for boilers, heating value of 28
  - percentage of water in 28
  - quantity needed 31
  - use of, extent of 25, 28

Y.

- Yield of oil wells, conditions affecting 7, 8, 9
  - of sand from oil wells 22, 26

○